Statistics of Link Blockage due to Cloud Cover for Free-space Optical Communications using NCDC Surface Weather Observation Data

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ABSTRACT

Cloud opacity is one of the main atmospheric physical phenomena that can jeopardize the successful completion of an optical link between a spacecraft and a ground station. Hence, the site location chosen for a telescope used for optical communications must rely on knowledge of weather and cloud cover statistics for the geographical area where the telescope itself is located.

In this work, the effects of cloud cover on an optical link are statistically described, considering ten observation sites at locations in the southwestern United States, from California to Texas. The data used for the preparation of this work are surface observation data provided by the National Climatic Data Center (NCDC).

NCDC provides hourly information on the cloud coverage of an observation site. Using proper algorithms, these data give a statistical description of link blockage over the ten selected observation sites. Statistics averaged over a number of years for each observation site are presented. Cloud coverage statistics for two and three site diversity are also given for a ground network of optical telescopes. Finally, it is shown quantitatively how the use of two or three telescopes can improve the probability of completion of an optical link and how to select the right locations for a ground network of telescopes in the southwestern United States.

SECTION 1 – INTRODUCTION

Free space optical satellite communications may be a viable alternative to radio frequencies because of their inherent technological advantages of high data rate, low power consumption, low mass, and small size components[1]. However, while inter-satellite optical links are facilitated *in vacuo*, the atmosphere greatly affects the completion of a successful space to ground (and vice versa) optical link because of the interaction between the transmitted optical beam and the atmospheric channel itself[2].

Particularly on Earth, the atmosphere adversely affects the optical link in a number of ways[3]. Gases and aerosols present in the atmosphere attenuate the optical signal by absorption and scattering[4]. Clear-sky turbulence changes the air refractive index causing distortion and wandering of the optical beam[5]. Finally, when clouds are in the line-of-sight between a satellite and a receiving (or transmitting) telescope, the completion of a satellite link is jeopardized owing to the cloud opacity[6]. Therefore, the choice of a site location for an optical telescope for optical communications must depend on, among a number of other factors, the knowledge of weather and the cloud coverage statistics of the geographical area where the telescope will be located.

In this work, we present a study characterizing the cloud coverage in the southwestern United States. This study considers ten different sites whose locations span the range from California to Texas, and it presents an analysis of cloud coverage records of these sites over a number of years. Descriptions of the selected sites are presented in Section 2. The data used for this study are surface observation data provided by the National Climatic Data Center (NCDC).

The design of a space-to-ground (or vice versa) optical link relies on the knowledge of the statistical characterization of the atmospheric channel. Therefore, we present statistics, averaged over a number of years, of clear, scattered, broken, and overcast sky. A more rigorous definition of those terms will be presented in a next section of this work. Operating two or more telescopes simultaneously (site diversity) greatly increases the possibility of successful completion of an optical satellite link because, in doing so, the greater probability that the sky is clear (or favorable) in one of the two (or three) sites will be exploited. Of course, for site diversity, the locations of the telescopes must be carefully selected in such a way that the weather patterns they experience are not only favorable but also anti-correlated. In this paper, therefore, as a result of the diversity statistics, we present indications about the proper selection of locations which most advantageously can house optical telescopes for site diversity.

SECTION 2 – SITE SELECTION

The United States Southwest is home to a large number of telescopes due to its dry weather, which manifests itself in a limited number of cloudy days with respect to other areas of the United States (and North America in general). Such a large geographical area, however, does not present a uniform weather (and cloud coverage) pattern during the year. For instance, while California experiences dry summer periods and storms during the winter, Arizona and New Mexico are mainly affected by stormy summer seasons. Therefore, our intent in this study is also to understand the variation and the correlation of cloud coverage in this area. To accomplish this goal, we have selected ten NCDC observation stations in the region in an area from California (Edwards Air Force Base, 101 km northeast of Los Angeles) to the border between New Mexico and Texas, as indicated in Figure 1. The maximum distance between sites is 1241 km (from Edwards to Roswell). There are several reasons for the selection of these particular observation sites. The first one, as already noted, is the intention to cover the relatively dry southwest region. Another reason is to select sites that are near telescope facilities. For example, at Table Mountain (CA) NASA/JPL is installing a telescope for optical communications,

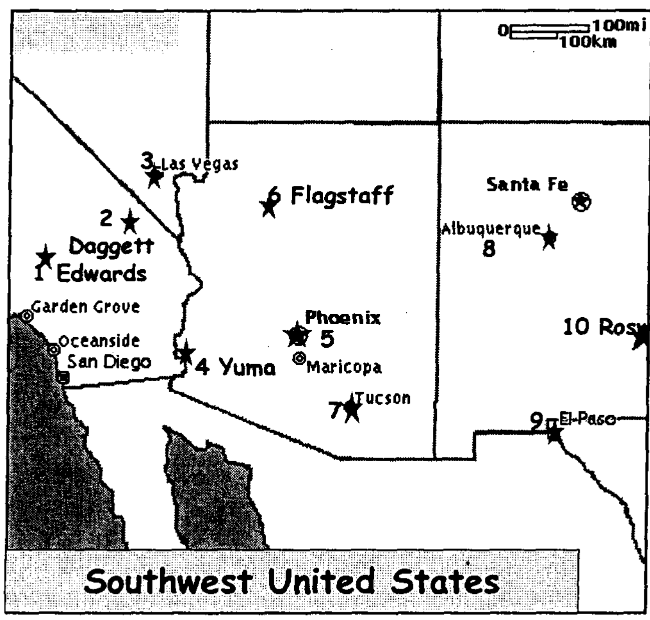


Fig. 1. Site Locations (denoted by stars) in the United States Southwest for which cloud coverage statistics has been characterized in this work.

and therefore we selected the observation station of Edwards Air Force Base, CA, which is in the vicinity of Table Mountain Observatory (65 km). Finally, we selected observation sites that are near locations or peaks that can be considered for the future installation of optical telescopes[7]. The selected locations are: (1) Edwards Air Force Base, CA. (2) Daggett Airport, CA.; (3) Las Vegas McCarran International Airport, NV. (4) Yuma International Airport, AZ. (5) Phoenix Sky Harbor International Airport, AZ.; (6) Flagstaff Pulliam Airport, AZ.; (7) Tucson International Airport, AZ. (8) Albuquerque International Airport, NM.; (9) El Paso International Airport, TX.; (10) Roswell Industrial Airpark, NM.

Most of the NCDC observation centers are located at airports or other locations with relatively modest elevations. By contrast, telescopes are located at higher elevations (usually mountain peaks). Therefore, one may expect (and take into account) different sky visibility conditions between mountain peaks and lower elevation areas in their proximity. For instance, fog and smog do not usually appear at higher elevations because they remain constrained by the inversion layer. Moreover, at higher elevations, mountains may cut off lower clouds, while sometimes the orographic effects of the mountains (usually for elevations between 3000 and 4000 m) may induce clouds to be trapped and localized.

As a last consideration about the selected sites, we would like emphasize the relationship between the size of the geographical area here studied and the distance between the Earth and a satellite. As we already pointed out, the greatest distance between two sites is 1241 km (Edwards–Roswell). Keeping this distance in mind, one may envision, for example, a communication scenario with a satellite transmitter for optical communication having a field of view on the order of 50 μrad. Under these conditions, during a deep space mission at a distance of one astronomical unit (150 million km), the laser transmitting towards the Earth can cover an area six times larger than the one considered here. The same is not true for a satellite in low Earth orbit. However, in this case the time delay necessary for the satellite to pass from Edwards to Roswell is on the order of a few minutes. Therefore, in both of these communication link scenarios, the results of cloud coverage site diversity statistics can be used for optical link design without lack of accuracy.

SECTION 3 – DATA PROCESSING

3.1 NCDC data archives

As already indicated, the cloud coverage data used in this report are provided by National Climate Data Center (NCDC)[8], which is the sole Agency Record Center for the Department of Commence. The NCDC collects, prepares, and distributes climate data regarding the United States, and it is also responsible for the United States branch of the World Data Center (along with Russia, Japan, and China).

Among the different types of environmental and weather observations collected and maintained by the NCDC, the work presented here is specifically based on the elaboration and processing of surface observation data. Surface observations are meteorological data that describe the climate of an area (or a site) where an observation station is located. Surface observations indicate, for each site, temperature, humidity, precipitation, snowfall, wind speed and direction, atmospheric pressure, visibility, and other kinds of weather conditions, including obscurations. The observations are (in general) made hourly, recorded, and collected by a certified operator. The data that we analyzed are in a format DATSAV3 (NCDC designation).

Essentially, the DATSAV3 format consists of rows of data, where each row contains the weather observations made at a specific moment of the day. To indicate the cloud coverage of the celestial dome, a station operator uses standardized requirements specified by the *Federal Meteorological Handbook*[9]. According to these requirements, an operator during an observation specifies the cloud coverage in "eighths" or "oktas" that are assigned according to the following numeric code: "0" when no clouds are present in the celestial dome (clear sky); "2" when the celestial dome is less than half covered ($0 <$ cloud coverage $\leq 4/8$) (scattered sky); "7" when the celestial dome is less then 7/8 covered ($4/8 <$ cloud coverage $\leq 7/8$) (broken sky); "8" when clouds completely cover the celestial dome, except perhaps a small portion (overcast sky).

3.2 NCDC data processing and the year-minute vector

For each observation station and each single year, the DATSAV3 data obtained by the NCDC are saved in the ASCII file format. We selectively retained only the information concerning the station identification number, observation time, and cloud coverage. Each year of observation of each station was saved as a single ASCII file. Therefore, each single year of data for each station is represented by a matrix of three columns (station identification number, time of observation, oktas of cloud coverage) and a variable number of rows corresponding to the total number of yearly observations. One must consider that although the observations are recorded in GMT, the number of observations vary greatly from year to year and from station to station (usually in a range from 6000 to 9500 rows); and therefore, the observation data are not synchronized among all the stations. To synchronize the yearly observation data and to facilitate the elaboration of the statistical data we introduced the year-minute vector, which is described next.

Each matrix of yearly data of a determinate year of a determinate station is converted to a vector with a length (or number of elements) equal to the total number of minutes in a year (525,600 or 527,040 for leap year). This vector was termed the year-minute vector. In other terms, the j-th element of the year-minute vector corresponds to the j-th minute of the year, and the numerical data contained in the j-th element corresponds to the eighths describing the cloud coverage at the j-th minute of the year.

As already stated, an NCDC operator records the station climate in general every hour. Moreover, observation records of different stations are not synchronized among themselves. Therefore, we need an algorithm to fill a year-minute vector from the information of the hourly observations of a matrix of yearly data. In order to accomplish this task, we first assume that the cloud coverage was constant during the interval between two consecutive observations. Then we fill the minutes of the time interval between two consecutive observations with the eighths (or other information) number of the first observation. When this time interval is more than two hours, we consider that it is not statistically accurate to use only one observation to describe such a time amount; therefore we fill this time gap of minutes with a flag number (we used the number 15) indicating that data are missing.

Table 1
Look-up table used for the two-site diversity algorithm.

Site 1	Site 2	Diversity
0	0	0
0	2	0
0	7	0
0	8	0
0	15	0
2	2	2
2	7	2
2	8	2
2	15	2
7	7	7
7	8	7
7	15	7
8	8	8
8	15	8
15	15	15

By using the year-minute vector representation it is relatively easy to extract the statistical information[10] concerning the site and the year of cloud coverage visibility, clear sky amount, etc. For instance, to calculate the total time (or amount) of clear sky in a year, we just count the zeroes of the vector. A similar approach is used to calculate monthly statistics. Moreover, the year-minute vector representation of the cloud coverage of an observation station greatly facilitates the calculation of diversity statistics between two (or more) sites. Consider, for instance, two year-minute vectors each describing the yearly cloud coverage at two generic sites, Site 1 and Site 2. The diversity year-minute vector (*i.e.,* a third vector) is obtained by comparing each corresponding element of the year-minute vectors of Site 1 and Site 2 and selecting the one for which cloud coverage is the more favorable. The lookup table in Table 1 presents the selection rules adopted to choose the more favorable condition among corresponding elements of the year-minute vectors of Site 1 and Site 2.

SECTION 4 – SINGLE SITE AND TWO-SITE DIVERSITY STATISTICS

4.1 Single and Two-site diversity statistics: 1991-1993 and 1997-1999

Initially we obtained 27 years worth of data from NCDC for the ten observation stations (1973-1999). However, in order to have consistent statistics, we considered only years in which the percentage of missing data is at most of the order of one and a half months (13% of the year-time amount). Moreover, we considered only years with missing data distributed over the years (i.e. years with an entire month of missing data were disregarded). These principles led us to restrict our study to six years 1991-1993 and 1997-1999 only. Finally, owing to the proximity of Edwards to the Table Mountain Observatory where during 2002 NASA/JPL will install a telescope for optical communications, emphasis will be made on the presentation of data involving the observation station of Edwards itself[11].

In Table 2 we present and compare the improvement of average yearly amount of clear sky of two-site diversity over single-site. Figure 2 compares the average cumulative distribution of the cloud coverage for single observation site and two-site diversity regarding Edwards and Roswell. Two-site diversity greatly increases the yearly amount of clear sky (66.57%), and for cloud coverage less than 4/8 (91.14%) with respect to the single site. Owing to their proximity to telescope facilities, another interesting case to consider is two-site diversity between Edwards and Tucson (*i.e.* Mount Lemmon Observatory, Tucson, AZ), as presented in Figure 3. Even in this case, two-site diversity proves very effective presenting an overall improvement over Tucson and Edwards with clear sky amount of 61.01% and 90.82% for cloud coverage less then four eighths.

Table 2

Two-site Diversity for 1991-1993 and 1997-1999: average amount of clear sky (%). The bold numbers in diagonal refer to single site statistics.

	Edwards	Daggett	Las Vegas	Yuma	Phoenix	Flagstaff	Tucson	Albuq.	El Paso	Roswell
Edwards	**26.83**	45.53	51.87	41.39	48.35	50.49	61.01	49.10	58.76	66.57
Daggett	45.53	**41.47**	56.69	50.04	55.55	58.91	68.79	58.44	66.60	74.91
Las Vegas	51.87	56.69	**46.51**	54.66	57.96	59.65	68.00	58.41	67.61	75.08
Yuma	41.39	50.04	54.66	**28.83**	44.54	52.81	57.66	48.22	57.18	66.36
Phoenix	48.35	55.55	57.96	44.54	**36.95**	55.66	57.14	50.19	58.61	68.23
Flagstaff	50.49	58.91	59.65	52.81	55.66	**40.68**	63.42	55.98	65.30	68.81
Tucson	61.01	68.79	68.00	57.66	57.14	63.42	**49.85**	58.18	62.29	68.45
Albuq.	49.10	58.44	58.41	48.22	50.19	55.98	58.18	**33.33**	54.14	63.12
El Paso	58.76	66.60	67.61	57.18	58.61	65.30	62.29	54.14	**44.71**	65.70
Roswell	66.57	74.91	75.08	66.36	68.23	68.81	68.45	63.12	65.70	**55.03**

Because Edwards has the average lowest clear sky amount among the ten locations, one should expect that other locations could offer higher yields of clear sky amount for two-site diversity. In fact, best results in two-site diversity involve Roswell and Daggett (see Figure 4), or Roswell and Las Vegas (see Figure 5). In these two cases the clear sky amount is about 75%.

4.2 Average monthly statistics: 1991-1993 and 1997-1999

Cloud coverage data from each observation station present monthly variations that greatly differ during the year depending on the geographical area. For instance, while the clear sky amount was smaller during the winter in Southern California, the same was not true in New Mexico and part of Arizona, where clear sky amount was reduced during the summer months of July and August. Therefore, upon selection of proper locations, one should expect that in two-site diversity statistics the monthly variation of clear sky (and other cloud coverage conditions) would be more uniform over the year. To better prove this last statement, in this segment we discuss monthly variations of two-site diversity statistics involving Edwards, Daggett, Las Vegas, Tucson, and Roswell.

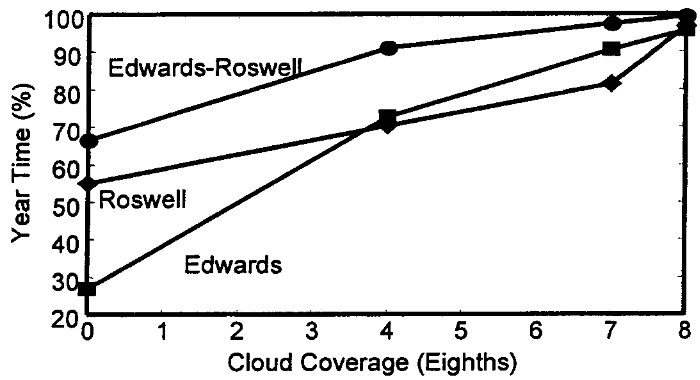


Fig. 2. Comparison between one site and two-site diversity for Roswell and Edwards for the years 1991-1993 and 1997-1999. Having installed an optical telescope at Table Mountain by NASA/JPL in the proximity of Edwards, Roswell is a potential location in whose proximity a telescope will enhance the two-site diversity with Table Mountain.

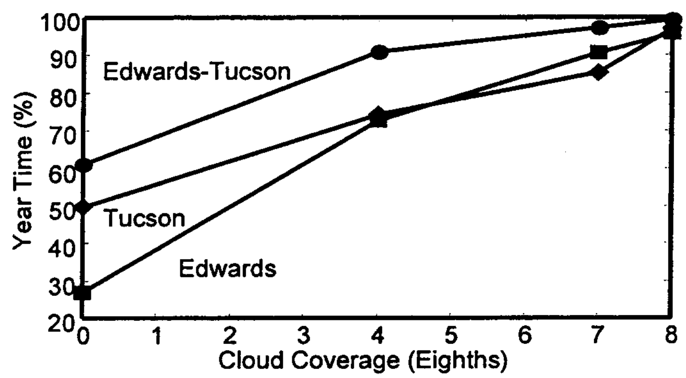


Fig. 3. Comparison between one site and two-site diversity for **Tucson** and **Edwards** for the years 1991-1993 and 1997-1999. In the figure is presented the average cumulative distribution of cloud coverage for Edwards, Tucson and site diversity Edwards-Tucson.

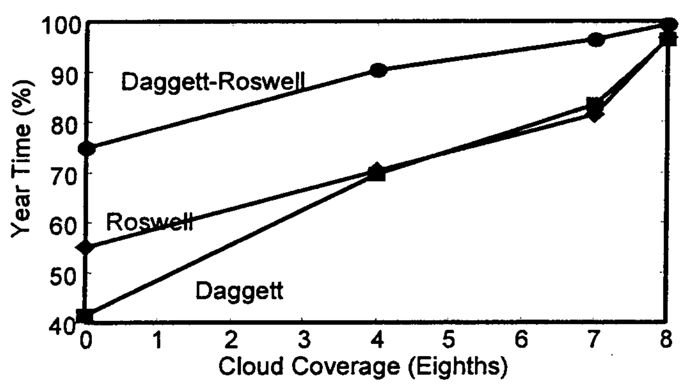


Fig. 4. Comparison between one site and two-site diversity for **Daggett** and **Roswell** for the years 1991-1993 and 1997-1999. In the figure is presented the average cumulative distribution of cloud coverage for Daggett, Roswell, and site diversity between Daggett-Roswell. Among the ten sites considered, Daggett and Roswell present the preferred condition for two-site diversity.

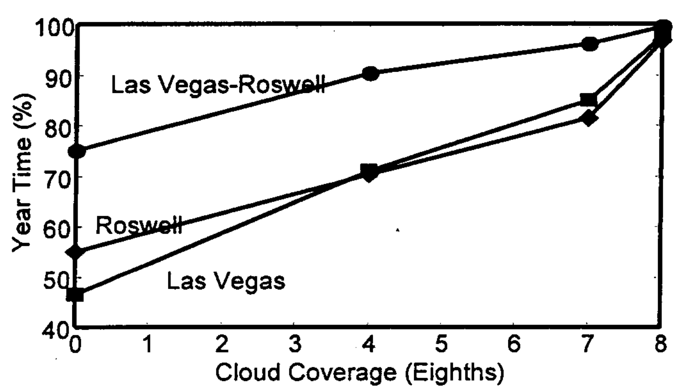


Fig. 5. Comparison between one site and two-site diversity for **Las Vegas** and **Roswell** for the years 1991-1993 and 1997-1999. In the figure is presented the average cumulative distribution of cloud coverage for Las Vegas, Roswell and site diversity between Las Vegas-Roswell. Among the ten sites considered, Las Vegas and Roswell present the preferred condition for two-site diversity.

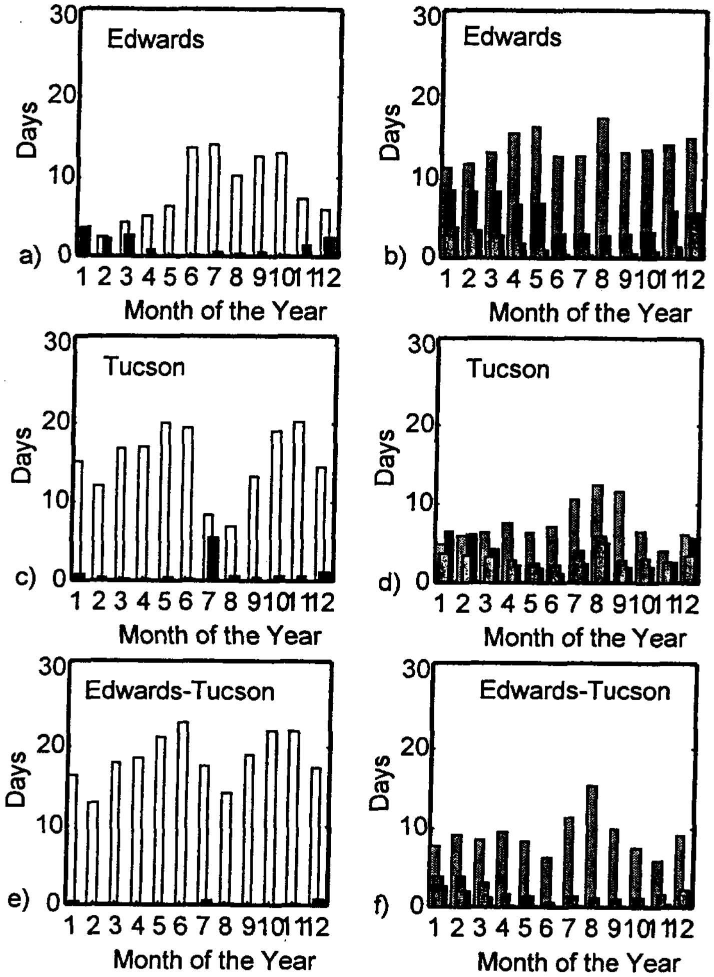
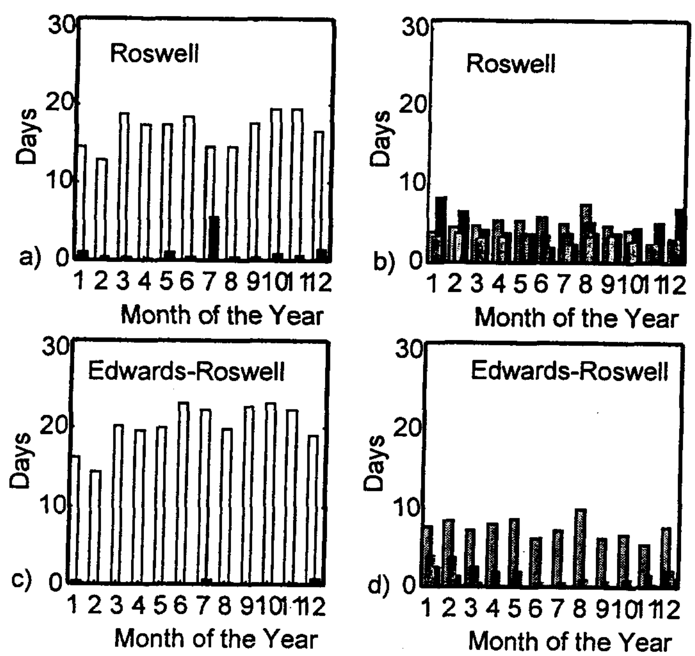


Fig. 6. Average monthly cloud coverage: comparison between one-site and two-site diversity for **Edwards** and **Tucson**. February is averaged over 28 days. **a), c)** and **e)** for each month is indicated in sequence the amount in days of clear sky (white bar), missing data (black bar) **b), d)** and **f)** for each month is indicated in sequence the amount in days of scattered (gray bar), broken (speckled bar) and overcast sky (black bar). The years studied are 1991-1993 and 1997-1999.

Fig. 7. Average monthly cloud coverage: comparison between one-site and two-site diversity for **Edwards** and **Roswell**. February is averaged over 28 days. **a)** and **c)** for each month is indicated in sequence the amount in days of clear sky (white bar), missing data (black bar) **b)** and **d)** for each month is indicated in sequence the amount in days of scattered (gray bar), broken (speckled bar) and overcast sky (black bar). The years studied are 1991-1993 and 1997-1999.



Average monthly variations of cloud coverage between Edwards and Tucson are presented in Figure 6. The differences between Edwards and Tucson are evident in Figures 6 a) and 6 c). Consequences of two-site diversity are shown in Figure 6 e), where during the months of winter, spring, and autumn the dominant clear-sky contribution to the statistics is given by Tucson, while during the summer Edwards compensates for the lack of clear sky at Tucson. A monthly variation is still visible in the two-site statistics for the clear sky, but overall we can observe an average amount of 15 days of clear sky all year round. Two-site diversity between Edwards and Roswell (Figure 7) presents more favorable conditions. In fact, the clear sky amount does not change much over the year. Except for the months of January and February, the average clear sky amount for the two-site diversity is approximately 20 days. As previously noted, Daggett and Roswell (Figure 8) along with Las Vegas and Roswell (Figure 9) are the most advantageous choices for two-site diversity. Las Vegas-Roswell two-site diversity presents minimal variation of clear sky amount over the year, with an average of 2/3 clear sky for each month.

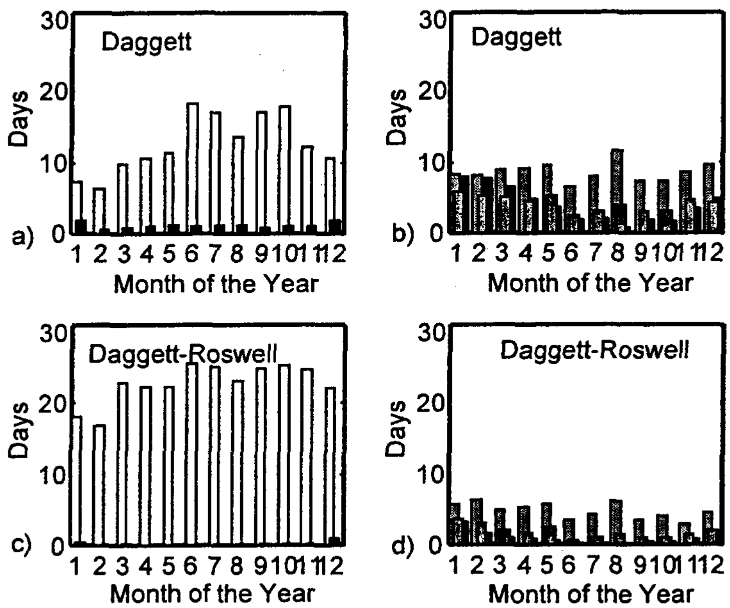


Fig. 8. Average monthly cloud coverage: comparison between one-site and two-site diversity for **Daggett and Roswell.** February is averaged over 28 days. **a)** and **c)** for each month is indicated in sequence the amount in days of clear sky (white bar), missing data (black bar). **b)** and **d)** for each month is indicated in sequence the amount in days of scattered (gray bar), broken (speckled bar) and overcast sky (black bar). The years studied are 1991-1993 and 1997-1999.

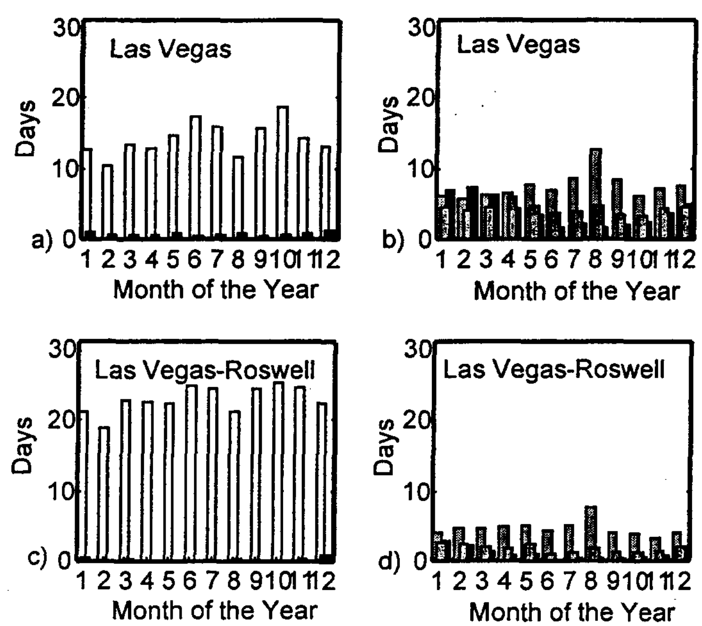


Fig. 9. Average monthly cloud coverage: comparison between one site and two-site diversity for **Las Vegas** and **Roswell.** February is averaged over 28 days. **a)** and **c)** for each month is indicated in sequence the amount in days of clear sky (white bar), missing data (black bar). **b)** and **d)** for each month is indicated in sequence the amount in days of scattered (gray bar), broken (speckled bar) and overcast sky (black bar). The years studied are 1991-1993 and 1997-1999.

SECTION 5 – THREE-SITE DIVERSITY STATISTICS

5.1 Three-site diversity: case study

Three-site diversity may offer a further improvement of clear sky (and clear plus scattered sky) over two-site diversity. Figure 10 presents some results of three-site diversity involving Edwards during the years 1991–1993 and 1997–1999. Among the curves in Figure 10, there is the cloud-coverage cumulative distribution curve which describes a case study with Edwards-Daggett-Tucson. For this configuration, the average clear sky amount is 70.6% during the year. However, the fact that Daggett is in the proximity of Edwards and that they both belong to the same climate area does not constitute a good choice for three-site diversity. As a result, for this site selection the benefits of having three stations operating simultaneously are greatly reduced. In fact, one may notice that during the same period of time, clear sky amount for two-site diversity of Tucson and Dagget is 68.79% which suggests that the addition Edwards to the other two stations does not help the overall statistics. Adding Roswell to Edwards and Tucson improves the two-site diversity performances as seen in Figure 3. For this last configuration, the average clear sky amount is 75.33% during a year with 19.52% scattered sky. However, if Edwards must be considered for three-site diversity, adding Roswell and Las Vegas gives the best contribution to enhance the clear sky statistics, with 77.54%.

Among the results analyzed here, the combination Daggett-Tucson-Roswell exhibited the best performance when considered for three-site diversity. In this case the yearly clear sky amount was of 81.24%, with a scattered sky amount of 13.34%. Incidentally, one may notice in Figure 1 that in this last configuration Tucson is symmetrically distant from the other two locations (each branch is of the order of 600 km) and moreover all three locations were representative of three distinct climatic zones.

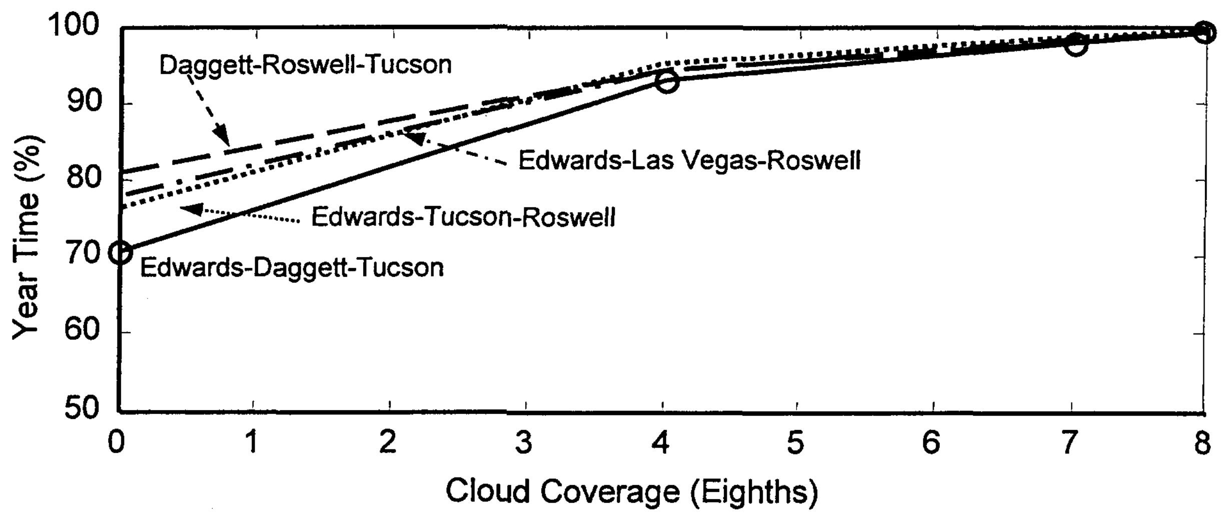


Fig. 10. Three-site diversity average cloud coverage statistics for Edwards-Daggett-Tucson (solid curve), Edwards-Tucson-Roswell (dotted curve), Edwards-Las Vegas-Roswell (dash-dotted curve), and Daggett-Roswell-Tucson (dashed curve). The years studied are 1991-1993 and 1997-1999. The piece-wise cumulative distribution curves are shown.

5.2 Three-site diversity: monthly cloud coverage

In this section we present results of monthly variations of cloud coverage for the same examples of three-site diversity analyzed in Figure 10.

Essentially, one should hope, after selecting the proper locations for three-site diversity, extended durations of clear sky, with minimal monthly variation. For Edwards-Daggett-Tucson, a yearly variation of monthly amount for clear sky is still detectable, with relatively minimal amounts in January, February, and August, as seen in Figure 11 a). During these months, the clear sky amount was in the range of 15-20 days. During the other months of the year it exceeded 20 days. For Edwards-Tucson-Roswell, the clear sky amount exceeded the 20 days with the exception of February (17 days). A reduction of the clear sky amount is detectable during August and the winter months, Figure 11 b).

Monthly variation of the clear sky amount was less accentuated for Edwards-Las Vegas-Roswell, as seen in Figure 11 c). In this configuration, February had only 19.11 days of clear sky amount (which, however, represented over 68% or the time during the month of 28 days), with the other months well beyond 20 days presenting a peak of 25.57 days in July.

The combination Daggett-Tucson-Roswell shows a similar trend of less variation, with an evident incremental increase of clear sky during the months of March, April, and May, Figure 11 d).

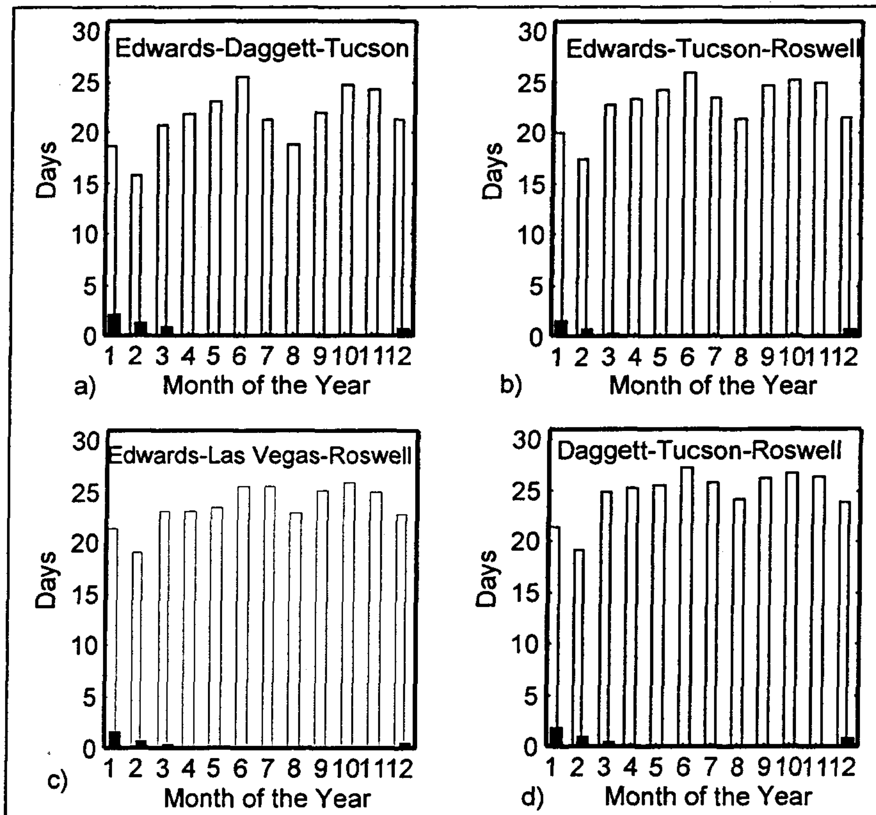


Fig. 11. Three-site diversity: average monthly clear sky for **a) Edwards-Daggett-Tucson, b) Edwards-Tucson-Roswell., c) Edwards-Las Veagas-Roswell, d) Daggett-Tucson-Roswell.** February is averaged over 28 days. For each month is indicated in sequence the amount in days of clear sky (white bar), missing data (black bar).

SECTION 6 – CONCLUSIONS AND FUTURE WORK

In this work we analyzed the cloud cover surface observation data from NCDC of related to ten sites in the southwestern United States. Using the surface observations we were able to calculate a statistical representation of cloud coverage for single site, two-site diversity, and three-site diversity. A key strategy for the calculation of our data is the creation of year-minute vectors, which are single vectors for which the number of elements is equal to the number of minutes of the year they describe. Each element of the year-minute vector gives information about cloud coverage at that specific minute of the year. Our year-minute vector representation greatly facilitated the determination of yearly statistics of cloud coverage and correlation coefficients among the ten different sites.

Two-site diversity statistics clearly showed improvement over the single observation site statistics. By selecting a proper pair of sites among the 45 available combinations, we also demonstrated that two-site diversity statistics presented favorable periods of clear sky that were more uniform over the months when compared to single-site statistics. For instance, Las Vegas-Roswell, during the years 1991–1993 and 1997–1999, presented clear sky amount of about 75% as compared to the single site amount of 46.51% for Las Vegas and 55.03% for Roswell, Table 2.

Besides the overall improvement of the sky visibility, further analysis of data, also has shown that site diversity can be a robust solution against anomalies in the climate patterns that may affect the performance of a single telescope. To better explain this last concept, one may consider the hypothetical case of two telescopes: one located in the proximity of Edwards (*e.g.,* Table Mountain) and the other in the proximity of Tucson (*e.g.*, Mount Lemmon) during the year 1997. Table 2 indicates that on average one should expect a yearly amount 28.83% of clear sky at Edwards and 49.85% in Tucson. However, under the influence of "El Niño", the cloud coverage in both locations greatly differed from the average during this year. In fact, during 1997 at Edwards only 19.39% of the time the sky was clear, while at Tucson clear sky amount was 61.36% while the overall diversity clear sky was 66.9%. Therefore, the unusual climate pattern caused by "El Níño" affected the two locations in an opposite way, and while the visibility of a telescope in the proximity of Edwards was greatly reduced, in Tucson the visibility condition was enhanced.

A further improvement with respect to two-site diversity is given by three-site diversity. For instance, statistics show that by adding Tucson (with 61.36% of yearly clear sky) to Las Vegas and Roswell, the clear sky amount is almost 80% compared to 75% for two-site diversity. The best overall results were observed for the triplet Daggett-Tucson-Roswell with 81.28% clear sky.

As a result of our investigation, one may notice that the average yearly clear sky amount improves on the order of tens of percent for two-site diversity over single site for two properly selected locations. However, the additional improvement for three-site diversity compared with two-site diversity may not be as dramatic. System engineers should carefully evaluate the importance of a few percentage numbers in considering whether they can justify the expenses that the use of a third telescope would entail in order to reach a very high availability of the atmospheric channel at optical wavelengths.

Finally, among the sites characterized here, it was not possible to observe an amount of clear sky close to 100% in any (single, two-site diversity or three-site diversity) configuration. This result suggests that the study presented here based upon NCDC surface observation data be further expanded to other areas of the United States to find if this 100% limit of yearly clear sky is achievable by site diversity.

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SECTION 7 – REFERENCES

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