ASSESSMENT OF ELECTROMAGNETIC INTERFERENCE EFFECTS OF THE SOLANO WINDFARM

Final Report

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TABLE OF CONTENTS

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Executive Summary

The potential interference effects of 67 wind turbines (WTs) of the proposed Solano Windfarm on the performance of various electromagnetic systems operating in its vicinity have been assessed theoretically. Specific non-military systems considered are: five VOR (Very High-Frequency Omni Range) systems within 20 miles of the windfarm; nine microwave links; two earth stations (ES) receiving signals from geo-stationary satellites; 11, 3 and 9 TV Channels originating from San Francisco (SF), San Jose (SJ) and Sacramento (SAC); respectively; one cable TV (CATV) Head-end receiving the desired TV signals. In addition to these systems, there may be some radar, navigational and other microwave systems associated with the U.S. Navy and Air Force installations about five to ten miles from the windfarm. Since it is understood that the military outfits prefer to do their own assessment, these military systems are excluded from the present assessment. Any existing maritime navigational system is possibly more than ten miles from the windfarm; it is unlikely that their performance would be affected by the windfarm and, hence, they are also excluded from the assessment. AM and FM broadcast reception outside the windfarm should not be affected significantly; within the windfarm, the reception within a few rotor diameters of individual WTs may experience some unacceptable interference effects. These systems have also been excluded from the detailed assessment.

It is understood that a choice has not yet been made regarding the specific type of WTs to be used in the windfarm. Therefore, the interference assessment has been carried out for three candidate machines: MOD-2, MOD-5A and WTS-4. Windfarm interference effects to each of the systems named earlier have been assessed on the basis of known criteria, and the assessment of such effects on specific systems are summarized below.

(i) VOR Systems

The VOR systems will not experience any unacceptable effects due to the windfarm of MOD-2, MOD-5A or WTS-4 WTs or any combination thereof.

(ii) Microwave Links

The performance of all of the microwave links except Link 28CC, will not experience any unacceptable effects due to the windfarm of MOD-2, MOF-5A or WTS-4 WTs or any combination thereof. Similar comments apply to the performance of Link 28CC provided that Site 43 is either modified (as recommended) or eliminated.

(iii) Earth Stations

The performance of the two earth stations will not experience any unacceptable effects due to the windfarm of MOD-2, MOD-5A or WTS-4 WTs or any combination thereof.

(iv) Television Reception

Interference to television reception or TVI effects have been assessed at Cordelia, Vallejo and Benicia located about 5 miles from the windfarm, and in four regions A, B, C and D representative of the residential homes in the immediate vicinity of the windfarm.

The city of Fairfield being more than 6 miles from the center of windfarm, it is expected that the TV reception there will not be significantly affected by the windfarm. For this reason, the TVI effects at Fairfield were not specifically assessed. In addition, the interference effects on the performance of a CATV Head-end have also been assessed. The TVI assessment has been performed on the assumption that all TV signals originating from the three cities SF, SJ and SAC are available for reception at the assessed areas and at the CATV Head-end. The interference effects to reception are assessed as follows:

(a) Reception at Cordelia

TVI effects on the reception on all TV Channels from SF, SAC and SJ would be acceptable with MOD-5A and WTS-4 or any combination thereof, but would be unacceptable with MOD-2 on Channel 2 from SF.

(b) Reception at Vallejo

TVI effects on the reception of all TV Channels from SF and SJ would be acceptable with MOD-2, MOD-5A and WTS-4 WTs or any combination thereof. Effects on the reception of TV Channels from SAC would be acceptable with MOD-5A or WTS-4, but would be unacceptable on Channel 3 with MOD-2.

(c) Reception at Benicia

TVI effects on the reception of all TV Channels from the three cities would be acceptable with MOD-2, MOD-5A or WTS-4 WTs or any combination thereof.

(d) Reception at A, B, C and D

None of the regions would be completely immune to unacceptable TVI effects on all TV Channels and for all three types of WTs. The effects are summarized as follows:

Windfarm Type	TVI Effects
MOD-2	acceptable at C
	unacceptable at A,B,D
MOD-5A	acceptable at C
	unacceptable at A,B,D
WTS-4	acceptable at A,B
	marginally acceptable at D
	unacceptable at C

The above assumes the use of properly oriented directional TV receiving antennas. With a poor antenna the reception at A,B,C and D will be unacceptably affected by varying amounts on almost all Channels and for all types of WTs. The reception on all Channels at sites within the windfarms using any of the three WTs would most probably be unacceptably affected by varying amounts.

(e) Reception of CATV Head-end

The TVI effects produced would be unacceptable on Channels 44 and 54 for MOD-2, unacceptable only on Channel 54 (from SF) for MOD-5A, and acceptable on all Channels for WTS-4.

(f) General Comments

Among the three candidate WTs, the MOD-2 machine has the largest equivalent scattering area and it is not surprising that unacceptable or worst TVI effects are caused by the windfarm of 67 MOD-2 WTs. It is conceivable that with a judicious combination of MOD-2 and other machines (i.e., the windfarm not consisting of MOD-2 only) such effects may be lessened considerably for the large residential areas of Cordelia, Vallejo and Benicia. This would require more study.

It is also appropriate to make some comments with regards to the unacceptable TVI effects obtained for specific cases. The TVI assessment has been conducted under the following two key assumptions: (a) the ambient TV signals at the turbine sites are about 20 dB larger than those at the receiving sites; (b) all of the identified TV Channel signals are available for reception in the areas of interest. Further study should be conducted to ascertain the validity of these assumptions, and also to determine the severity of unacceptable TVI effects for specific cases.

Finally, the assessment has been carried out for a windfarm consisting of 67 WTs. With a reduced size windfarm the resultant interference effects will be lessened, and the following comments apply to a windfarm, say, of 21 machines:

(i) TV reception at Cordelia, Vallejo and Benicia and at the CATV Head-end will not be affected significantly by MOD-2, MOD-5A or WTS-4 or any combination thereof.

(ii) Although the TVI effects at A,B,C and D will be lessened (compared to the larger farm), none of these areas would be completely immune to unacceptable effects for any of the three machines.

1. Introduction

The present report is concerned with an assessment of the potential effects of interference produced by the proposed Solano Windfarm on the performance of various electromagnetic systems operating in its vicinity. The assessment is carried out theoretically, and the specific systems considered are: (i) VHF Omnidirectional Range or VOR, navigational systems, (ii) microwave links, (iii) Earth Stations (ES) receiving signals from geostationary satellites, (iv) television (TV) reception, and (v) Cable TV (CATV) Head-end installations for receiving the desired TV signals.

In addition to the electromagnetic systems named above, there may be numerous radar, navigational and other microwave systems associated with the U.S. Navy and Air Force installations about five to ten miles from the windfarm. Possible impact on the VOR system at Travis Air Force Base has been assessed under (i) mentioned above. There appear to be no microwave link paths originating from the military bases which intersect the windfarm. Any other on-base electromagnetic systems being over five miles from the windfarm, the probability of any interference with their performance will be minimal and, hence, have not been considered. Since it is understood that the military outfits prefer to do their own assessment, it is felt to be adequate to inform the commanders of the various installations of the proposed windfarm and offer cooperation in assessing any electromagnetic impact if they so desire. Also, there may be some maritime systems operating over the shipping lane extending east from San Pueblo Bay in Suisun, Grizzly and Honker Bays. Since the distance of these systems from the windfarm is more than about ten miles, it is unlikely that their performance will be affected. Undoubtedly, there are some AM- and FM-broadcast systems operating in the area. Reception of AM broadcast signals is usually vulnerable to various locally generated interference effects. The highest AM broadcast frequency being 1.6 MHz ($\lambda \simeq 188$ m), it is unlikely that the windfarm will produce any adverse effects unless the receiver is located within a few rotor diameters of a WT. The reception of FM broadcast signals would be even less vulnerable to such effects. For these reasons, these two systems have also been excluded from the present assessment.

The interference effects of concern arise because of the time varying multiplath created by a rotating wind turbine (WT) blade [1]. The primary signal is generally reflected in an almost specular (mirror-like) manner off a blade to produce a secondary (interfering) signal. The strength of the latter is proportional to the equivalent scattering area (A_e) of the blade and decreases with increasing distance from the turbine; at any given distance it also increases with increasing frequency. If this secondary signal is sufficiently strong, it may combine with the primary signal at the receiver to produce unacceptable interference effects on the performance of the system under consideration. A key point is that because the reflection is specular, any given receiver will be affected only when the blade is suitably oriented. The nature and amount of the interference effects observed by the receiver depend on the nature of the electromagnetic system and its associated signal processing logic.

It should be pointed out that the observed interference caused by the assembly of WTs in the windfarm will generally be statistical in nature [2] depending on a number of parameters. However, we shall use non-statistical analyses to estimate the effects produced by the WTs, either singly or together, on each of the electromagnetic systems mentioned earlier. Our assessment will thus pertain to the maximum effects that may occur in a given case under worst conditions.

2. Background Information

Various information needed for the assessment is described in the present section.

2.1. Windfarm and Its Environment. The proposed windfarm will occupy a 5000-acre site approximately five miles ENE of Vallejo, CA, as indicated on the road map section shown in Fig. 1. This is a relatively unpopulated region with hills rising to about 1100 feet above sea level, used mainly for grazing cattle. From an aerial map of the area it has been found that there are approximately 186 buildings within the farm area, most (or all) of which are presumed to be residential. In addition, there are three populated communities within a radius of six miles of the center of the windfarm. Starting with the smallest population to the largest, these communities are: Cordelia, Benicia and Vallejo located NE, S and SW of the windfarm, respectively.

A topographical map of the windfarm showing the placement of WTs is given in Fig. 2 where the center of the windfarm is identified as CF at the junction of the dotted square sections numbered 35, 36, 2 and 1; it should be noted that each dotted section in Fig. 2 is one mile square. As presently planned, 67 wind turbines (WTs) numbered 1 through 67 in Fig. 2 will be deployed along the ridge lines and tops of hills within the windfarm; later, the number of WTs may be increased up to 150. The 21 WTs, identified by circles around the corresponding numbers in Fig. 2, generating about 100 MW of power are to be installed during the first phase; the remaining WTs are identified by triangles in Fig. 2. The regions indicated by P-P in Fig. 2 are the potential locations for future WTs. For illustrative

Solano Windfarm

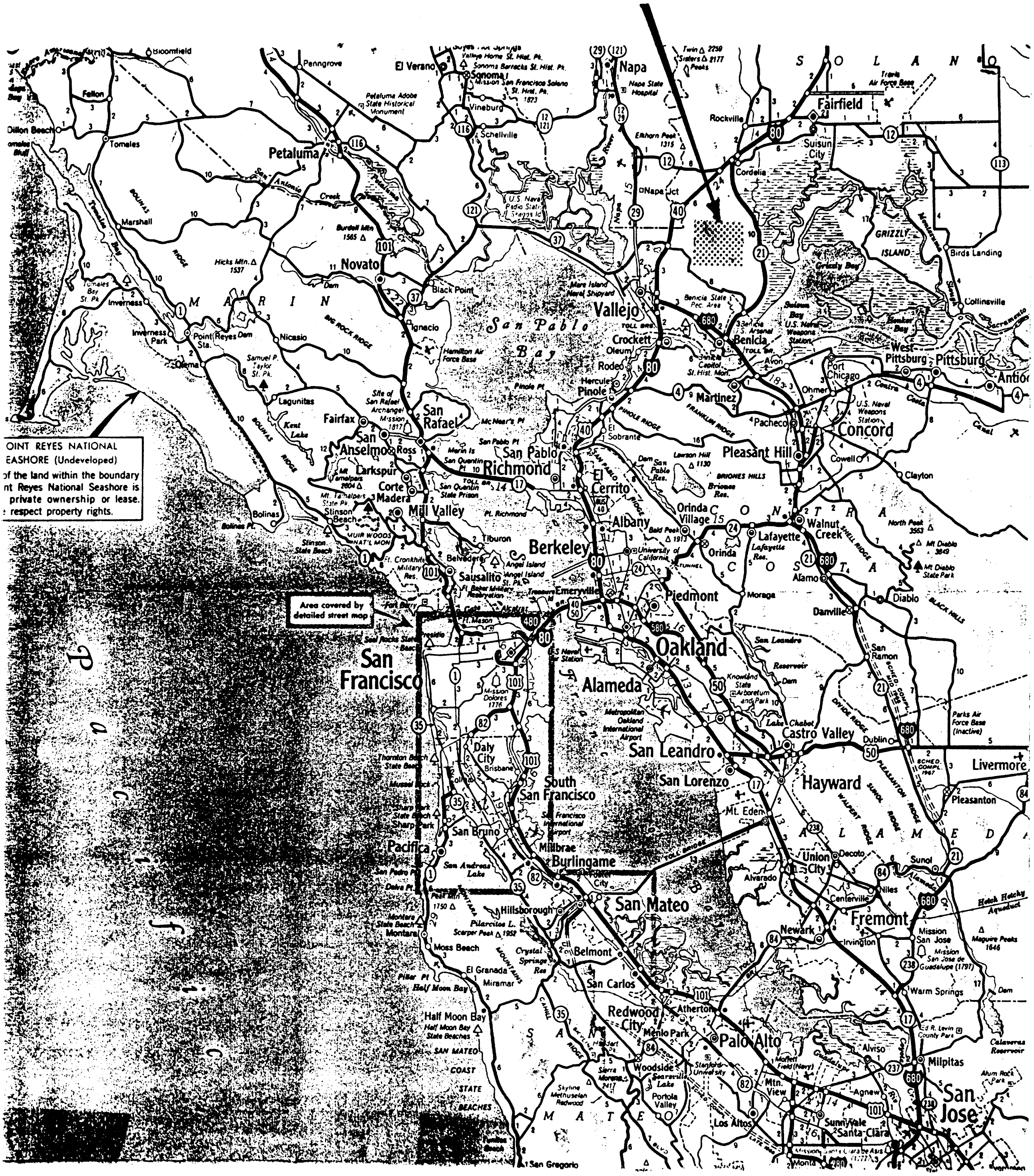


Fig. 1: Road map of the San Francisco Bay area, showing the general location of the Solano Windfarm, indicated by □.

(Scale: 1 inch = 6 miles)

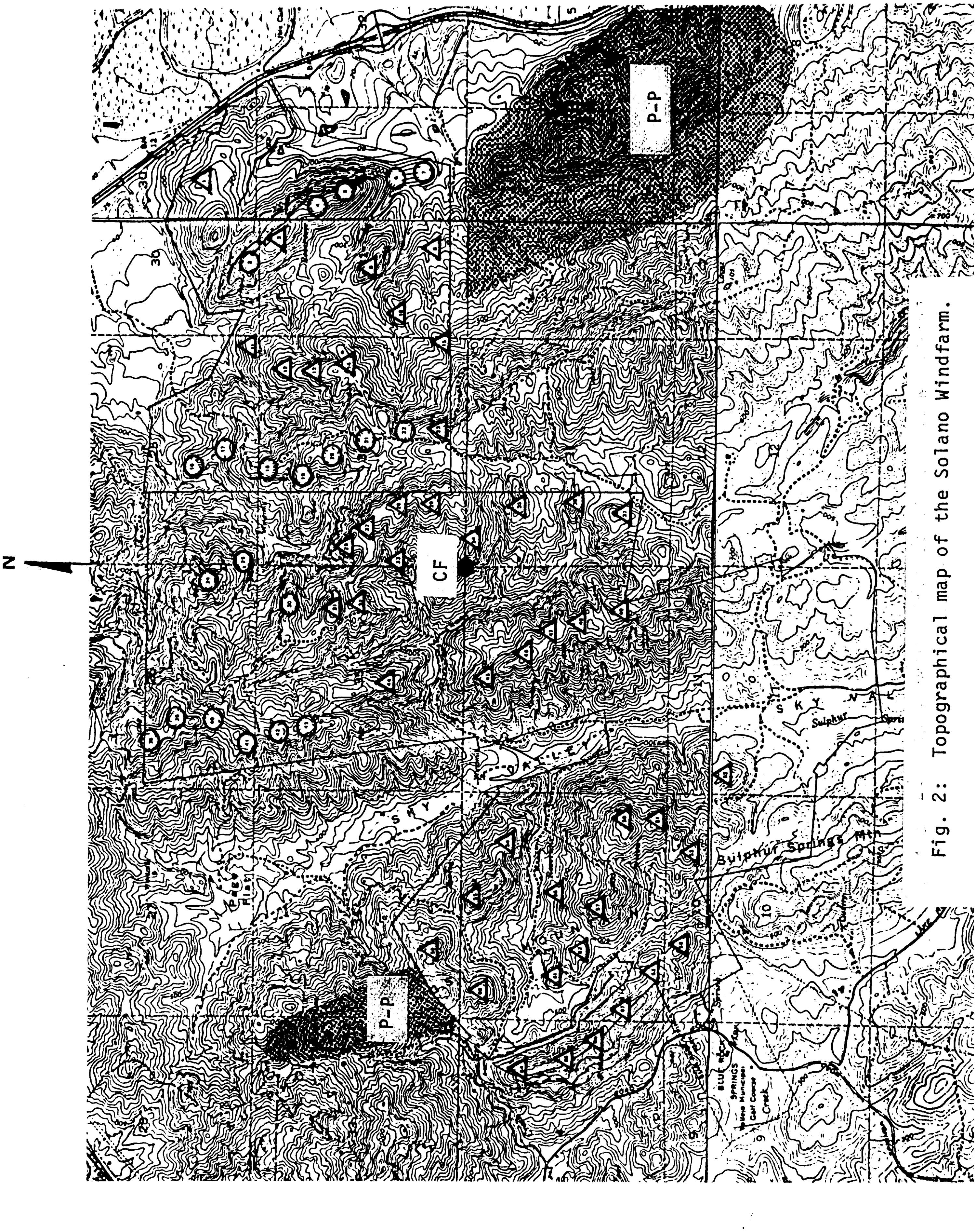


Fig. 2: Topographical map of the Solano Windfarm.

purposes we shall simplify the representation of the windfarm by a cross-hatched region. Using the cross-hatched region we indicate (Fig. 3) the distribution of the 186 buildings in the windfarm in blocks of one square mile sections. The number within parentheses appearing in each square section is the number of buildings in that section, and the other number is its average elevation (in feet above sea level); the dot within each section represents the region in that section having the largest concentration of residential homes. Points A, B, C and D, marked in Fig. 3, are representative of the regions containing the most dwellings within, and in the immediate vicinity of, the windfarm. For the purpose of assessing the television interference (TVI) effects at A, B, C, and D and at the three communities of Cordelia, Benicia and Vallejo, we show their location with respect to the windfarm in Fig. 4 where the number in each square-mile section is that of the corresponding section of the original topographical map from which Fig. 4 has been prepared. About 2.5 miles from CF and just outside the windfarm there is a tower (about 45 feet high) containing antennas which receive available TV signals for a CATV service. The location of the CATV antenna tower (or Head-end) is shown as CATV in Fig. 4. The points marked ES in Fig. 4 represent the location of two satellite earth stations to be discussed later. The three directional radials (originating from CF) in Fig. 4 refer to the directions and distances of Sacramento (SAC), San Jose (SJ) and San Francisco (SF) where the transmitters of the TV signals available in the area are located. The characteristics of these TV transmitters are described in the next section.

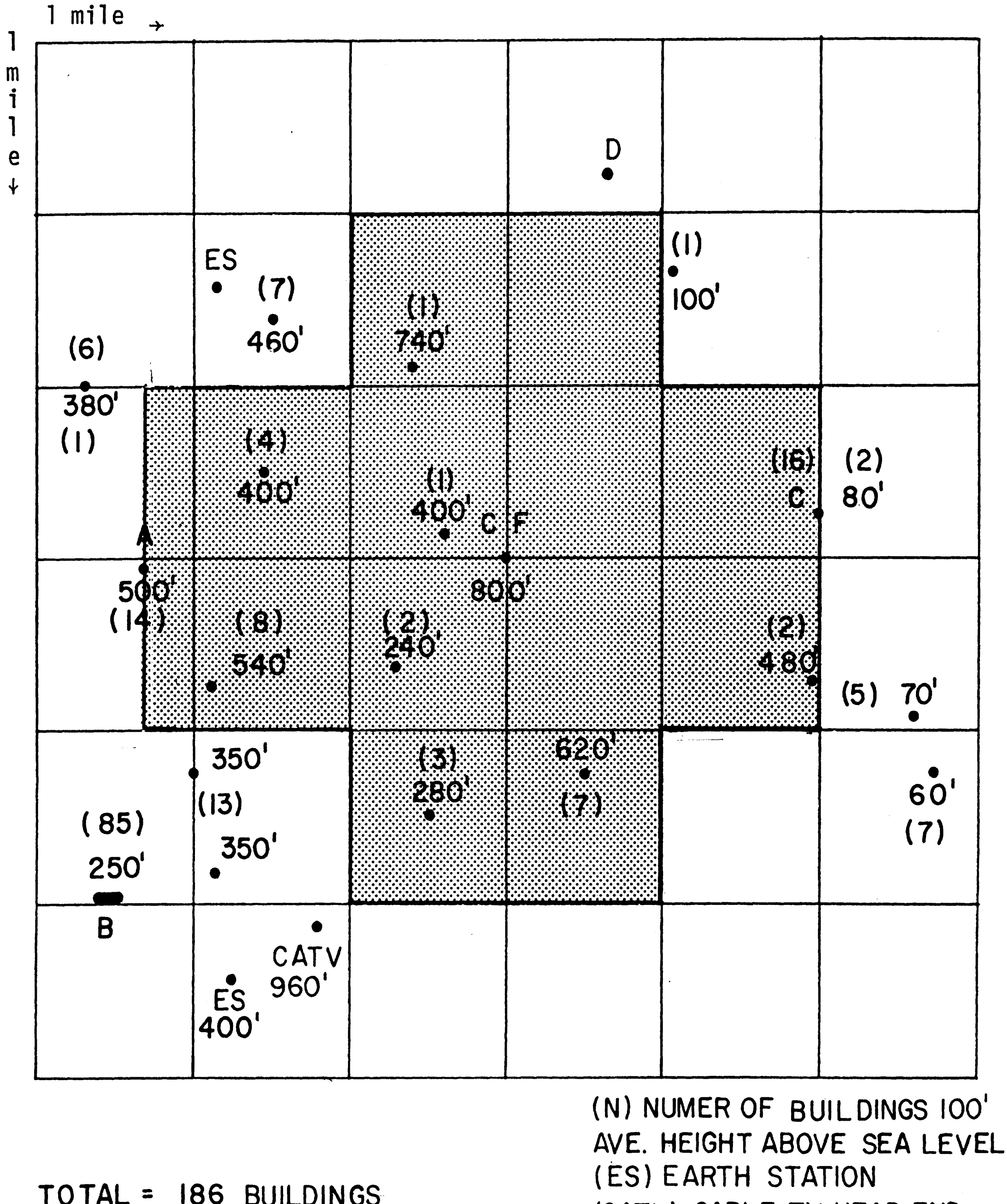
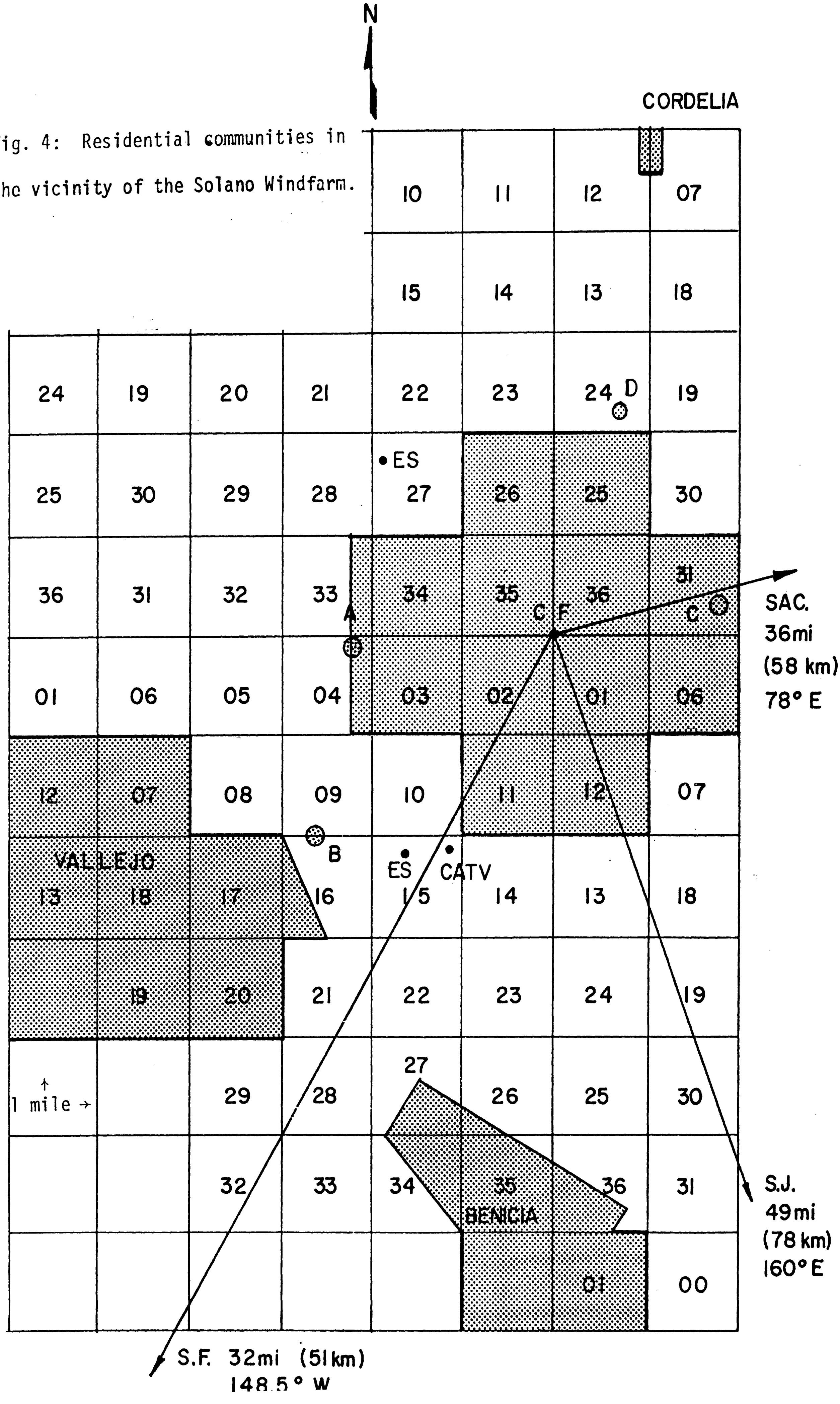


Fig. 3: Buildings in the vicinity of Solano Windfarm.

Fig. 4: Residential communities in the vicinity of the Solano Windfarm.



2.2 TV Stations. As mentioned above, TV signals available in the windfarm area originate from transmitters located in Sacramento, San Jose and San Francisco at distances of 36, 49 and 32 miles, respectively, from the center of the windfarm complex. It is expected that residents in the windfarm area and nearby commmunities observe TV programs originating from these three cities. Tables 2.1 through 2.3 list the available TV Channels originating from the cities, their network affiliation, transmitting antenna location and height above sea level. Although the companies owning the TV stations listed in Tables 2.1 through 2.3 specify the expected service (in the windfarm area) on most of the TV Channels as grade A or B, the terrain in the windfarm area is quite hilly, and all of the TV Channels may not be available at all of the places. Also, due to shadowing and other effects, the ambient signal levels on some (or all) of the Channels may be very weak at places located in the valleys.

2.3 VOR Stations. Throughout the country the Federal Aviation Administration (FAA) maintains VHF Omni Range (VOR) ground stations which provide navigation information to aircraft in flight. From FAA maps of VOR ground stations in the area, five conventional stations have been identified within 20 miles (approximately 32 km) of the windfarm. A portion of a standard map showing two VOR stations within about ten miles of the windfarm is reproduced in Fig. 5. The approximate directions and distances of the five VOR stations within 20 miles of the windfarm are shown in Table 2.4. A VOR system operates at a single frequency in the range 108 to 118 MHz [3],

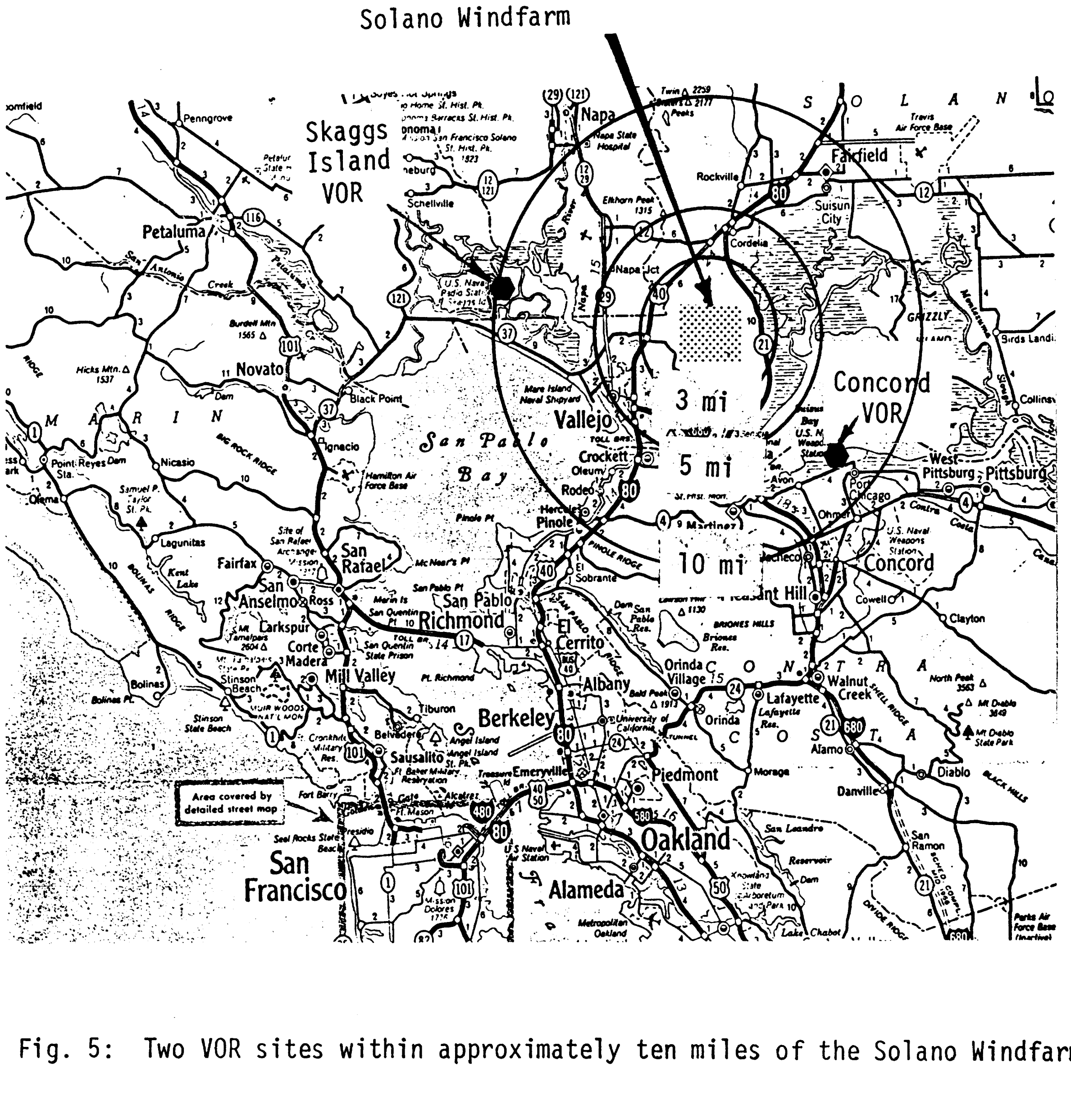


Fig. 5: Two VOR sites within approximately ten miles of the Solano Windfarm.

Table 2.1 TV Channels Originating from Sacramento

Station	Channel No.	Twr. Ant. Ht. above sea level	Location Latitude (N) Longitude (W)	Rad. Power Video Audio
KCRA	3	1548'	38°14'48" 121°29'59"	P_v = 100 kW P_a = 20 kW
Educat.	6	1544'	38°14'48" 121°30'3"	55 kW
KXTV	10	1548'	38°14'48" 121°14'48"	P_v = 309 kW P_a = 61.7 kW
KOVR	13	1549'	38°14'48" 121°29'59"	P_v = 218 kW P_a = 42.7 kW
KLOC	19	3080'	38°7'8" 120°43'21"	P_v = 5000 kW P_a = 1 kW
KMUV	31	1057'	38°14'20" 121°28'52"	P_v = 107 kW P_a = 55 kW
KTXL	40	998'	38°16'25" 121°30'11"	P_v = 1000 kW P_a = 124.5 kW

Table 2.2 TV Channels Originating from San Jose

Station	Channel No.	Tr. Ant. Ht. above sea level	Location Latitude (N) Longitude (W)	Rad. Power Video Audio
KN-TV	11	4079'	37°6'40" 121°50'34"	P_v = 80.65 kW P_a = 9.48 kW
KGSC	36	2794'	37°29'05" 121°15'53"	P_v = 2735 kW P_a = 273.5 kW
Educ. KTEH	54	2707'	37°29'07" 121°51'57"	P_v = 661 kW P_a = 132 kW

Table 2.3 TV Channels Originating from San Francisco

Station	Channel No.	Tr. Ant. Ht. above sea level	Location Latitude (N) Longitude (W)	Rad. Power Video Audio
KTVU	2	1808'	47°45'20" 122°27'5"	P_v = 100 kW P_a = 14 kW
KRON	4	1811'	37°45'20" 122°27'5"	P_v = 100 kW P_a = 15 kW
KPIX	5	1811'	37°45'20" 122°27'5"	P_v = 100 kW P_a = 10 kW
KGO	7	1811'	37°45'20" 122°27'5"	P_v = 316 kW P_a = 63 kW
---	9	1810'	37°45'20" 122°27'5"	P_v = 316 kW P_a = 63 kW
KDTV	14	1476'	37°41'17" 122°26'01"	P_v = 257 kW P_a = 257 kW
KEMO	20	1481'	37°41'17" 122°26'07"	P_v = 2500 kW P_a = 170 kW
KTSF	26	1539'	37°41'12" 122°26'3"	P_v = 2510 kW P_a = 500 kW
Educ.	32	1810'	36°45'20" 122°27'5"	P_v = 1330 kW P_a = 265 kW
KVOF	38	1499'	37°41'15" 122°26'04"	P_v = 2584 kW P_a = 417 kW
KBHK	44	1811'	37°45'20" 122°27'5"	P_v = 2200 kW P_a = 871 kW

Table 2.4 VOR ground Stations near the Windfarm

Designation	Direction from the Windfarm	Distance from the center of the Windfarm
Concord	SE	9 miles (14.5 km)
Skaggs Island	NW	11 miles (17.7 km)
Travis AFB	NE	12 miles (19.3 km)
Sausalito	SW	20 miles (32.2 km)
Oakland	S	20 miles (32.2 km)

but for computational purposes we shall assume that its operating frequency is f = 120 MHz, with wavelength λ = 2.5 m.

2.4 Microwave Links. A number of microwave link paths used for point-to-point communication purposes criss-cross the windfarm area. Some of the links are overhead, i.e., the points of origin (or Head-ends) are located about 20 miles from the windfarm; a few links have one of their Head-ends located within or near the windfarm. Detailed technical information regarding the microwave links in the region was obtained from Spectrum Planning, Inc., of Richardson, TX, and is shown in Table 2.5 where the link paths are identified by a number such as 1,5 etc,; each identifying number is associated with the letters PSIT or CC where the former refers to Public Safety Industrial Transportation microwave link and the latter to Common Carrier microwave link path. Using the data shown in Table 2.5 we have prepared a map indicating the microwave links in the windfarm region as shown in Fig. 6, where it can be seen that Paths 7, 8 and 27 are overhead and the rest have one Head-end in the windfarm area. As can be seen from Table 2.5 all links use slightly different frequencies for reception and transmission, but for convenience of calculation we shall assume that each link operates at a single average frequency for both. Table 2.6 then shows the average frequency of operation assumed for the microwave links.

2.5 Earth Stations. Two earth stations communicating with geo-stationary satellites are located in the vicinity of the windfarm and are shown as ES in Fig. 6. The ES located in the square-mile section 28 is entitled Sky Valley and is operated by Western Union; the other, located in section 15, entitled Vallejo, is operated by the American Satellite Corporation. Each of the earth stations is

Table 2.5. Microwave Links in the Vicinity of the Windfarm.

Path 1 PSIT

CALL SIGN & OWNER	WAA893	CHEVTE	BENIC	CHEVTE
STATE & LOCATION	CA, CLAYTON		CA, BENICA	
LATITUDE & ELEVATION	37-53-30 N	3320 FT	38- 7-51 N	1160 FT
LONGITUDE	121-54-21 W		122- 8- 4 W	
AZIMUTH & DISTANCE	322.97 DEG	20.68 MI	142.83 DEG	33.28 KM
ANTENNA TYPE	PL8-65D		PL8-65D	
ANT GAIN & HEIGHT	42.3 DBI	65 FT	42.3 DBI	65 FT
XMIT POWER & LINE LOSS	30.0 DBM	0 DB	30.0 DBM	0 DB
TRAFFIC TYPE	420 CHANNEL MSG		420 CHANNEL MSG	
TRANSMIT FREQS 6655.0V			6815.0V	

Path 5 PSIT

CALL SIGN & OWNER	WAA894	CHEVTE	BENIC	CHEVTE
STATE & LOCATION	CA, RICHMOND		CA, BENICA	
LATITUDE & ELEVATION	37-56-33 N	480 FT	38- 7-51 N	1160 FT
LONGITUDE	122-24- 6 W		122- 8- 4 W	
AZIMUTH & DISTANCE	48.21 DEG	19.52 MI	228.38 DEG	31.42 KM
ANTENNA TYPE	PL8-65D		PL8-65D	
ANT GAIN & HEIGHT	42.3 DBI	65 FT	42.3 DBI	65 FT
XMIT POWER & LINE LOSS	24.0 DBM	0 DB	34.0 DBM	0 DB
TRAFFIC TYPE	420 CHANNEL MSG		420 CHANNEL MSG	
TRANSMIT FREQS 6635.0H			6715.0H	

Path 6 PSIT

CALL SIGN & OWNER	WAN816	CHEVTE	WEE708	CHEVTE
STATE & LOCATION	CA, CONCORD 1701		CA, BENICIA	
LATITUDE & ELEVATION	37-58-15 N	30 FT	38- 7-51 N	1160 FT
LONGITUDE	122- 3-20 W		122- 8- 4 W	
AZIMUTH & DISTANCE	338.72 DEG	11.84 MI	158.67 DEG	19.06 KM
ANTENNA TYPE	PL8-65D		PL8-65D	
ANT GAIN & HEIGHT	42.3 DBI	27 FT	42.3 DBI	65 FT
XMIT POWER & LINE LOSS	5.0 DBM	0 DB	19.0 DBM	0 DB
TRAFFIC TYPE	420 CHANNEL MSG		420 CHANNEL MSG	
TRANSMIT FREQS 6565.0V			6735.0V	

Table 2.5 (cont.)

Path 7 PSIT

CALL SIGN & OWNER	WCP885 UNDGRD	WCP886 UNDGRD
STATE & LOCATION	CA, ROUNDTOP	CA, VACA
LATITUDE & ELEVATION	37-50-49 N 1480 FT	38-24-55 N 2700 FT
LONGITUDE	122-11-57 W	122- 7- 3 W
AZIMUTH & DISTANCE	6.45 DEG 39.45 MI	186.50 DEG 63.49 KM
ANTENNA TYPE	P-972G	P-972G
ANT GAIN & HEIGHT	22.6 DBI 100 FT	22.6 DBI 30 FT
XMIT POWER & LINE LOSS	33.0 DBM 0 DB	34.0 DBM 0 DB
TRAFFIC TYPE	2 CHANNEL MSG	2 CHANNEL MSG
TRANSMIT FREQS	959.20H	955.60H

Path 8 PSIT

CALL SIGN & OWNER	KMP74 TUG	KMP76 TUG
STATE & LOCATION	CA, BERKELEY	CA, MT VACA
LATITUDE & ELEVATION	37-53- 5 N 1310 FT	38-24- 1 N 2760 FT
LONGITUDE	122-13-58 W	122- 6-26 W
AZIMUTH & DISTANCE	10.85 DEG 36.21 MI	190.93 DEG 58.27 KM
ANTENNA TYPE	P-972G	DB-496
ANT GAIN & HEIGHT	22.6 DBI 18 FT	13.5 DBI 20 FT
XMIT POWER & LINE LOSS	36.0 DBM 0 DB	37.0 DBM 0 DB
TRAFFIC TYPE	6 CHANNEL MSG	6 CHANNEL MSG
TRANSMIT FREQS	954.00V	957.60V

Path 18 CC

CALL SIGN & OWNER	SKY V WU	WQP60 WU
STATE & LOCATION	CA, SKY VALLEY	CA, CORDELIA
LATITUDE & ELEVATION	38- 9-39 N 460 FT	38-14-51 N 1300 FT
LONGITUDE	122-11-18 W	122-12- 9 W
AZIMUTH & DISTANCE	352.65 DEG 6.03 MI	172.65 DEG 9.70 KM
ANTENNA TYPE	UHX8-107DRF	UHX8-107DRF
ANT GAIN & HEIGHT	46.5 DBI 194 FT	46.5 DBI 150 FT
XMIT POWER & LINE LOSS	37.0 DBM 0 DB	37.0 DBM 0 DB
TRAFFIC TYPE	VIDEO	VIDEO
TRANSMIT FREQS	11385.0U 11665.0H 11625.0U	10775.0U 10975.0H 11015.
	11425.0H 11305.0U 11585.0G	10735.0G 11175.0U 10895.
	11545.0U 11345.0G 11225.0U	10935.0U 11135.0H 11095.
	11505.0H 11465.0U 11265.0G	10815.0H 10855.0U 11055.

Table 2.5 (cont.)

Path 27 CC

CALL SIGN & OWNER	KNM54 WTCI	VOLLM1 PACTI
STATE & LOCATION	CA, MT VACA	CA, VOLLMER PEAK
LATITUDE & ELEVATION	38-24-55 N 2740 FT	37-52-58 N 1810 FT
LONGITUDE	122- 6-39 W	122-13-11 W
AZIMUTH & DISTANCE	189.21 DEG 37.20 MI	9.14 DEG 59.87 KM
ANTENNA TYPE	HP8-107D	HP8-107D
ANT GAIN & HEIGHT	46.4 DBI 25 FT	46.4 DBI 30 FT
XMIT POWER & LINE LOSS	DBM DB	37.0 DBM 0 DB
TRAFFIC TYPE	VIDEO	VIDEO
TRANSMIT FREQS		11135.0V 11055.0V

Path 28 CC

CALL SIGN & OWNER	1BA718 AMSAT	MTVACA AMSAT
STATE & LOCATION	CA, SULPHUR SPRING	CA, S MT VACA
LATITUDE & ELEVATION	38- 6-50 N 955 FT	38-24-21 N 2704 FT
LONGITUDE	122-10-30 W	122- 6-29 W
AZIMUTH & DISTANCE	10.23 DEG 20.46 MI	190.27 DEG 32.93 KM
ANTENNA TYPE	UHX12-107DRF	UHX12-107DRF
ANT GAIN & HEIGHT	49.8 DBI 35 FT	49.8 DBI 30 FT
XMIT POWER & LINE LOSS	24.0 DBM 0 DB	37.0 DBM 0 DB
TRAFFIC TYPE	DIGITAL	DIGITAL
TRANSMIT FREQS	10975.0U 10735.0V 10895.0U 11135.0U 10815.0U 11055.0U	11385.0U 11625.0U 11305. 11545.0U 11225.0V 11465.

Path 30 CC

CALL SIGN & OWNER	WBA718 AMSAT	SULPHA AMSAT
STATE & LOCATION	CA, VALLEJO ES	CA, SULPHUR SPRING
LATITUDE & ELEVATION	38- 6-33 N 410 FT	38- 6-50 N 955 FT
LONGITUDE	122-10-57 W	122-10-30 W
AZIMUTH & DISTANCE	51.45 DEG .52 MI	231.45 DEG .84 KM
ANTENNA TYPE	UHX12-107DRF	UHX12-107DRF
ANT GAIN & HEIGHT	49.8 DBI 15 FT	49.8 DBI 35 FT
XMIT POWER & LINE LOSS	37.0 DBM 0 DB	-9.0 DBM 0 DB
TRAFFIC TYPE	DIGITAL	DIGITAL
TRANSMIT FREQS	10975.0G 10735.0H 10895.0G 11135.0G 10815.0G 11055.0G	11385.0G 11625.0G 11305.0 11545.0G 11225.0H 11465.

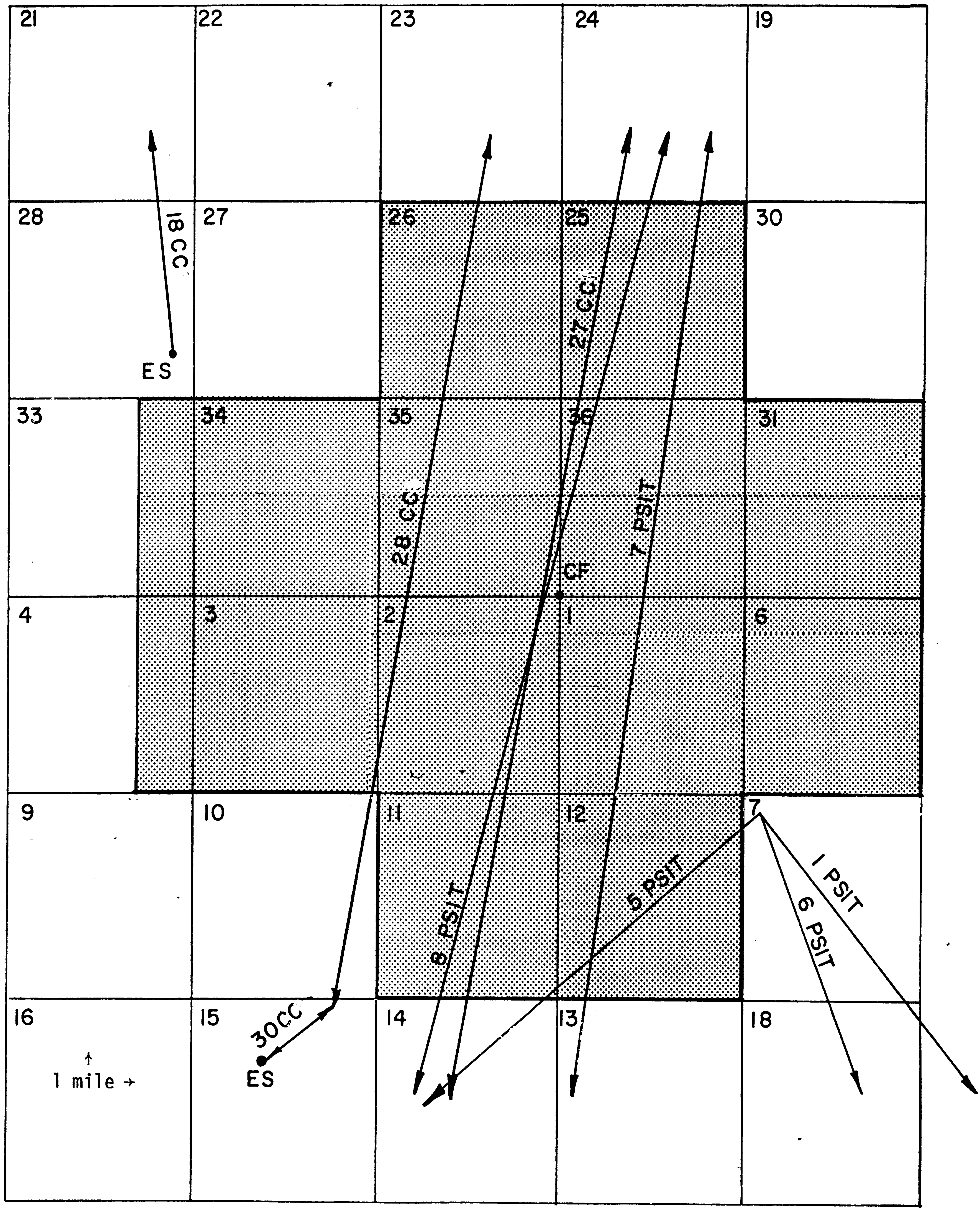


Fig. 6: Microwave links in the vicinity of the Solano Windfarm.

Table 2.6 Average Operating Frequency and Wavelength of the Microwave Links

Link (number)	Frequency (f)	Wavelength (λ)
7,8	1.0 GHz	30 cm, 1 ft
1,5,6	7.0 GHz	4.3 cm, 0.14 ft
27,28	10.0 GHz	3.0 cm, 0.1 ft
18,30	11.0 GHz	2.7 cm, 0.095 ft

equipped with large parabolic dish antennas (10 m and/or 15 m in diameter) which are normally directed at the desired stationary satellite located above the equator. Figure 7 shows the approximate azimuth orientations of the antenna beams A and B, communicating with the most easterly and westerly oriented satellites, respectively. The elevation angles of beams A and B are approximately 20 degrees and 40 degrees above the horizon.

2.6 Wind Turbines. It is understood that no decision has been made yet as to the exact type of wind turbine that will constitute the windfarm. However, it is believed that the WTs will belong to a class of current generation large horizontal axis machines referred to as MOD-2, MOD-5A, and WTS-4, of which the first two are upwind and the last is a downwind machine. Relevant information about these WTs needed for their electromagnetic interference assessment is given in Table 2.7. It should be noted that the blades of the all three turbines in Table 2.7 can be teetered by about six to nine degrees. WTS-4 has two blades installed with a coning angle of six degrees. The equivalent scattering area for the MOD-5A blade was obtained by taking into account the effects of a lightning arrestor assumed to consist of a one-edge metal treatment and metal-screen covered tip sections. The equivalent scattering area for the WTS-4 blade given in Table 2.7 refers to one blade.

3. Interference Assessment Procedure

The interference assessment which has been carried out is analytical and, in the case of those systems which are impacted, quantitative. The procedures used are based on the analyses and techniques developed by the Radiation Laboratory during our previous studies of electromagnetic interference produced by WTs, the details of which may be found in [1,4-6]. In the present section we

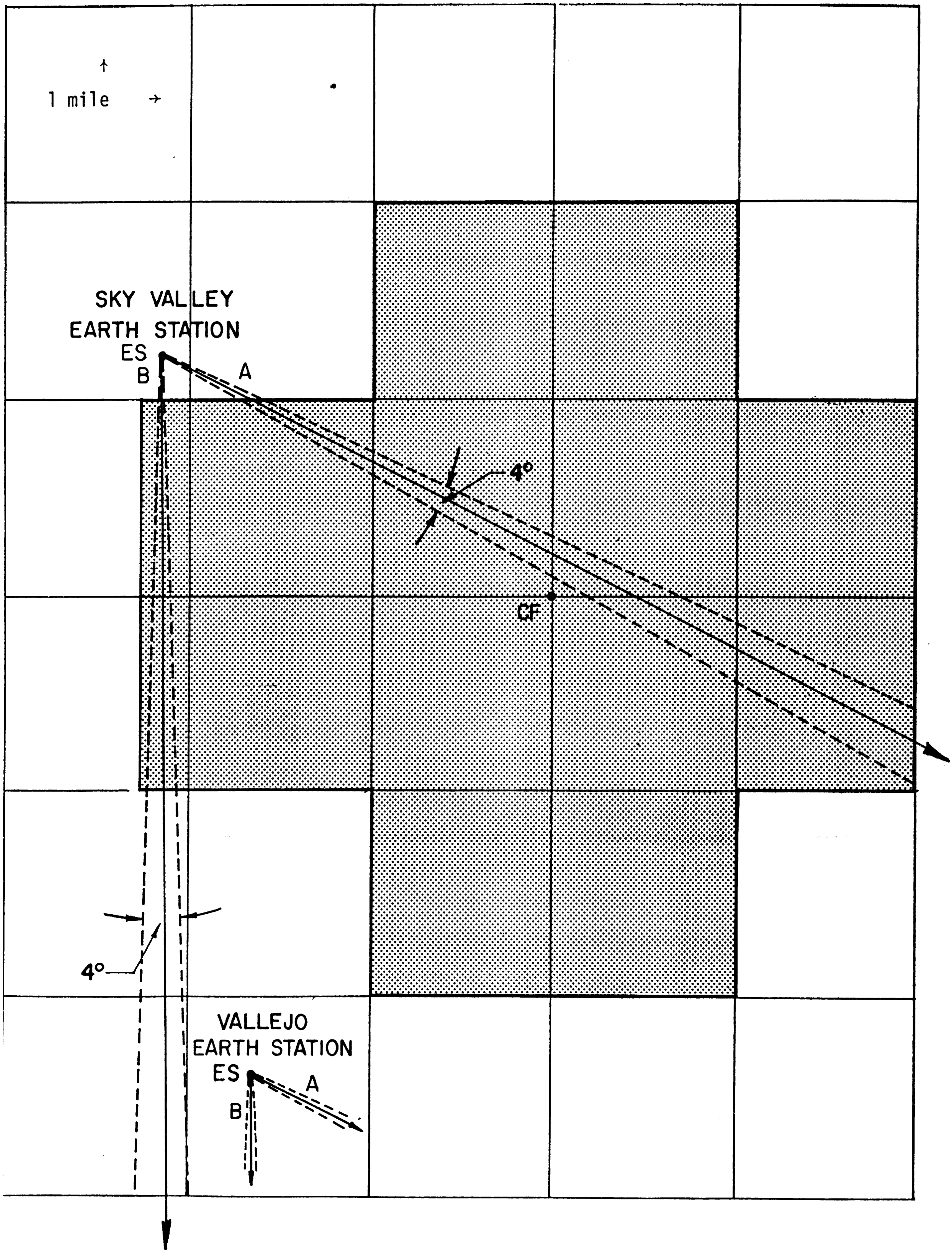


Fig. 7: Earth Stations in the vicinity of the Solano Windfarm.

Table 2.7 Relevant Information about the Candidate Wind Turbines

WT (type)	Tower Ht. h_{WT} (ft) (m)	1/2 Rotor Diameter D/2 (ft) (m)	$h_{WT}+D/2$ (ft) (m)	Equivalent Scattering Area A_e (ft^2) (m^2)	Equivalent Length L_e (ft) (m)
MOD-2	200 61	150 46	350 107	1507 140	207 63
MOD-5A	250 76	200 61	450 137	1076 100	207 ∿ 63
WTS-4	∿ 270 82	130 40	400 122	291 27	108 33

merely quote the basic criteria used to judge the acceptability (or unacceptability) of the interference effects produced in a given situation, and these same criteria are also used to judge the acceptability (or unacceptability) of a particular WT at a given site.

The basic parameter that is used to judge the effect of WT-produced interference on an electromagnetic system is

$$\Gamma = \frac{\text{amplitude of the interference signal caused by one WT}}{\text{amplitude of the desired (direct) signal}}, \quad (1)$$

where the fields are computed at the receiver of the system under consideration. As mentioned in the Introduction, the interference signal is produced by scattering off the WT blade(s), and in general

$$\Gamma \propto \frac{E_B}{E_R} \frac{A_e}{\lambda d}, \quad (2)$$

where E_B, E_R are the amplitudes of the ambient electric fields at the WT and the receivers, respectively,

λ is the operating wavelength and

d is the distance between the WT and the receiver.

Γ also depends in a rather complicated manner on the ambient signal strengths at the WT and receiver locations, and on the receiving antenna characteristics [1,4]. In our previous studies we developed approximate expressions for Γ under various situations, and these have been used for the present assessment. Assuming that the interference effects produced by the individual machines are additive in power, the total effect produced by N WTs is then judged by the parameter Γ_T:

$$\Gamma_T = \left[\sum_{1}^{N} \Gamma_n^2\right]^{1/2} ,$$

where Γ_n is that produced by the nth WT. In many cases we shall assume $\Gamma_1 = \Gamma_2 \ldots \Gamma_N = \Gamma$, and use

$$\Gamma_T = \sqrt{N}\,\Gamma . \tag{3}$$

In some cases only the machine(s) closest to the receiver cause most of the problem, but in other cases there can be many machines which contribute significantly to the total effect. The actual criteria (including the values of Γ_T or Γ) which are used to judge the interference effects depend on the electromagnetic system under consideration, and are discussed in the following sections.

3.1 Interference to VOR. In the vicinity of a VOR ground station the FAA prohibits [3] the existence of any tall scattering object which makes an angle more than 1.5° (for metal object) and 2.5° (for wooden or non-metallic object) at the phase center of the VOR antenna. It is also recommended that the amplitudes of any reflected or scattered interfering signal relative to that of the desired signal at the receiver not exceed 20 percent. We shall use the following acceptability criterion for assessing the effect of interference on VOR performance:

$$\Gamma_T \text{ (or } \Gamma) \leq 0.2 \text{ (or -14 dB)} . \tag{4}$$

3.2 Interference to Microwave Link. The satisfactory performance of a microwave link system requires that there be adequate clearance between the link path, i.e., the optical line-of-sight transmission path between the two link antennas, and any nearby scattering objects. It is often required [7] that all scattering objects lie outside the first few Fresnel zones as shown in Fig. 8, and in the present case we shall use the acceptability criterion

$$H \geq 3H_1 \quad . \tag{5}$$

The parameter H_1 is obtained from a knowledge of d, d_1 and the operating wavelength.

In addition to using the criterion given by Eq. (4), in some cases we have also calculated Γ_T (or Γ) to estimate the magnitude of the scattered (or interfering) signal relative to the desired one.

3.3 Interference to Earth Stations. Interference to an earth station (ES) communicating with a geo-stationary satellite has been assessed by using the Fresnel distance criterion, given by (5), used for the microwave links. We have also used the acceptability criterion

$$\Gamma_T \leq 0.01 \text{ (-40 dB)} \tag{6}$$

to estimate the level of interference signal at the earth station.

3.4 Interference to Television Reception. WT interference effects to TV reception generally appear in the form of video distortion occurring at twice the rotation frequency of the blade. The dominant

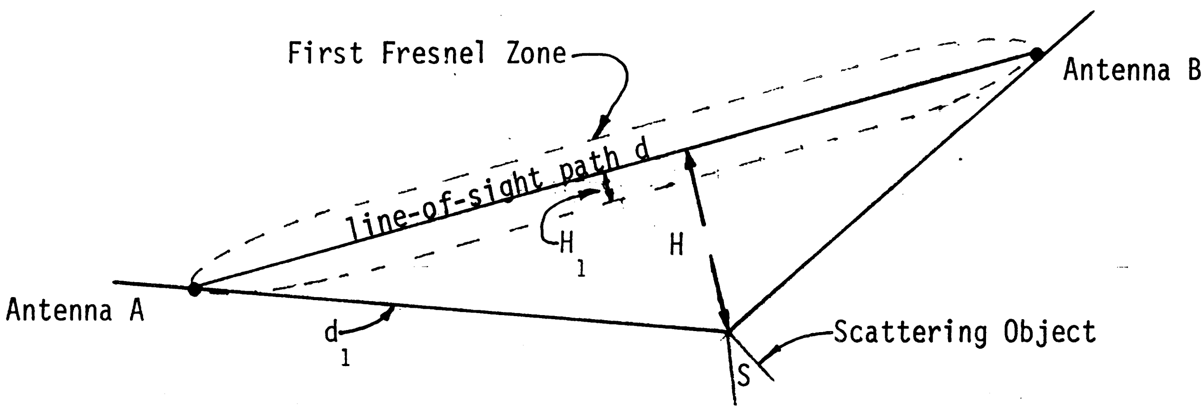


Fig. 8: Diagram showing a scattering object outside the first Fresnel zone of the link antennas.

H_1 = first Fresnel zone distance

H = clearance of S from the link path

parameter determining the interference by a WT is the equivalent scattering area of its blade. However, at a certain distance from the WT the maximum video distortion observed depends on the state of the WT blade (i.e., pitch, plane of rotation, etc.), the ambient signal strengths at the WT and the receiver, the characteristics of the receiving antenna, and on whether the receiver is located in the forward or backward region of the WT. In the backward region the directional property of the receiving antenna may be used to discriminate against the interference effects but in the forward region this cannot be done and hence the effects may be more severe.

When the blades are stationary the scattered signal may appear on the TV screen as a ghost whose position (i.e., separation from the direct picture) depends on the difference between the time delays suffered by the direct and scattered signals. A rotation of the blades then causes the ghost to fluctuate, and if the ghost is sufficiently strong, the resulting interference can be objectionable. In such cases, the received picture displays a horizontal jitter in sinchronism with the blade rotation. As the interference increases, the entire (fuzzy) picture shows a pulsed brightening, and still larger interference can disrupt the TV receiver's vertical sync, causing the picture to roll over ('slip') or even break up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering, primarily specular, off the broad fact of a blade, and is called the backward region interference. As the angle between the WT-transmitter and WT-receiver directions increases, the separation of the ghost decreases, and a somewhat greater interference is now required to produce the same amount of distortion. In the forward scattering region, when the WT is almost is line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals. The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases, the amount of interference depends on the strength of the scattered signal relative to the primary signal at the receiver, i.e., on the modulation index of the total received signal, and the modulation threshold is defined to be the largest value of the modulation index for which the distortion is still judged to be acceptable.

It can be shown [1,2,4,5] that in the case of television interference (TVI) caused by WTs, the parameter Γ_T (or Γ), defined earlier, can be interpreted as the amplitude modulation index m_T (or m) suffered by the received signal due to the scattering by the rotating WT blades. Judgement of TVI effects or the video distortion observed is made on the basis of m_T (or m).

In the backward region for all levels of ambient signals, and in the forward region where the ambient signal is weak, interference effects are judged to be acceptable if

$$m_T \text{ (or m)} \lesssim 0.15 \quad (\sim -17 \text{ dB}) \ . \tag{7}$$

For a receiver in the forward region where the ambient signal is strong, the corresponding criterion is

$$m_T \text{ (or m)} \lesssim 0.35 \quad (\sim -9 \text{ dB}) \ . \tag{8}$$

The above criteria are based on the subjective assumption [4] that the resultant video distortion is acceptable. For satisfactory performance of a CATV Head-end the requirement on the interfering signal is more severe [8] and we shall assume the following acceptability criterion:

$$m_T \text{ (or } m) \leq 0.05 \quad (-26 \text{ dB}) \quad . \tag{9}$$

4. Assessment of Interference

The windfarm interference effects on various systems are quantitatively estimated in the present section. The assessment includes the effects of 67 WTs which are presently planned to be installed in the windfarm; the effects of future WTs to be deployed in areas marked P-P in Fig. 2 are exluded from the present discussion.

As mentioned in Section 2.6, the windfarm may consist of MOD-2, MOD-5A, or WTS-4 machines or any combination of these three types of WTs. In the absence of definite information regarding the type of WT to be used, we shall assume the windfarm to consist of 67 identical WTs belonging to one of the above three types of machines.

4.1 Interference to VOR. The interference signal ratio Γ_T at the VOR receiver, produced by the windfarm, has been calculated for the Concord and Skaggs Island VOR systems located about 9 and 11 miles from the windfarm, respectively. Detailed calculations of Γ_T for specific cases are discussed in Appendix 1.

Γ_T values for the two VOR systems obtained for different machines are shown in Table 4.1 which indicates that for all types of WTs, the windfarm produces $\Gamma_T < -14$ dB, i.e., any interference

Table 4.1

Γ_T at a VOR Receiver Produced by the Windfarm

	Γ_T in dB, caused by the windfarm consisting of		
	WTS-4	MOD-2	MOD-5A
Concord VOR	-43	-28	-31
Travis AFB VOR	-41	-27	-30

effects produced would be insignificant. The other VOR ground stations being farther away from the windfarm (see Table 2.4), it is unlikely that their performance would be adversely affected by the windfarm.

4.2 Interference to Microwave Links. Assessment of interference to each of the microwave links in the vicinity of the windfarm (Fig. 6) has been carried out on the basis of Fresnel distance criterion mentioned in Section 3.2. Details of actual calculations required for a sample assessment are described in Appendix II. In the present section we present in tabular form the crucial assessment parameters associated with the offending WT sites for each link and comment on the acceptability of those sites for the link under consideration. The effects of WTs located in the two future sites P-P (see Fig. 2) have not been considered in the present assessment.

Sites listed in Table 4.2 are acceptable with MOD-5A; they are acceptable also with MOD-2 or WTS-4. It is concluded that the performance of Link 27CC would be unaffected by a windfarm of MOD-2, MOD-5A or WTS-4 or any combination of these three WTs.

Table 4.2

Assessment Parameters of Offending Sites for MOD-5A: Link 27CC

Site No.	ΔH (ft)	$3H_1$ (ft)
26	1125	210
33	1065	210
46	1065	210

Link 8 PSIT

Table 4.3

Assessment Parameters of Offending Sites for MOD-5A: Link 8 PSIT

Site No.	ΔH (ft)	$3H_1$ (ft)
26	885	654
33	845	654
48	805	654
49	785	654

The offending sites listed in Table 4.3 are acceptable with MOD-5A, and also with MOD-2 or WTS-4. The performance of Link 8 PSIT would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4 or any combination of these three WTs.

Link 7 PSIT

Table 4.4

Assessment Parameters of Offending Sites for MOD-5A: Link 7 PSIT

Site No.	ΔH (ft)	$3H_1$ (ft)
26	940	684
20	860	684
21	940	684

The offending sites listed in Table 4.4 are acceptable with MOD-5A, and also with MOD-2 or WTS-4. The performance of Link 7 PSIT would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4 or any combination of these three WTs.

Link 28 CC

Calculations needed for the assessment of interference to this link have been described in Appendix II.

Table 4.5

Assessment Parameters of Offending Sites for MOD-5A: Link 28CC

Site No.	Δr (ft)	$3H_1$ (ft)
39	550	117
40	520	114
41	520	112
42	280	111
43	50	108

Sites 39 through 42 are acceptable with MOD-5A and also with MOD-2 or WTS-4. Site 43 is unacceptable with any of the three machines. The performance of Link 28CC would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4 or any combination of these three machines provided that site 43 is (i) eliminated or (ii) moved to the west by at least 60 feet or to the east by at least 560 feet.

Links 1 PSIT, 6 PSIT, 5 PSIT

No offending sites are identified within $3H_1$ of the link paths. The performance of these three links would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4 or any combination of these three machines.

Link 18CC

As no offending sites are identified within $3H_1$ of the link path, the performance of this link would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4 or any combination of these machines.

Link 30CC

No offending sites exist in the vicinity of the link, and hence its performance would be unaffected by the windfarm consisting of MOD-2, MOD-5A or WTS-4, or any combination of these three machines.

4.3 Interference to Earth Stations. As shown in Fig. 7 there are two earth stations, named Sky Valley and Vallejo, in the vicinity of the windfarm. We shall assume that each earth station uses a 33 foot (10 m) diameter parabolic dish antenna at f = 5.0 GHz, i.e., λ = 0.2 ft (0.06 m); at this frequency the antenna typically has a beamwidth of 0.45°. If the interference effects are acceptable for this antenna, they would also be acceptable for the larger (49 ft or 15 m) antenna used by the two earth stations.

It can be seen from Fig. 7 that both the antenna beams A and B (or the link paths) pass above the windfarm; the dotted lines within ±2° of the beam directions denote regions in azimuth where offending WTs may lie.

Let us estimate the impact on the Sky Valley earth station. Using Figs. 2 and 7 it is found that there are approximately three and four offending WT-sites for beams A and B, respectively, at distances 2.6 miles (4.2 km) and 2.0 miles (3.2 km) from the station. The first Fresnel distances corresponding to these distances are:

$$d_1 = 2.6 \text{ miles} \qquad H_1 = 52 \text{ ft}$$

$$d_1 = 2.0 \text{ miles} \qquad H_1 = 46 \text{ ft}$$

The elevation (h_ℓ) of the two beams (or link paths) at these distances are:

$$h_\ell = 4996 \text{ ft}$$

$$\simeq 96\, H_1 \quad , \text{ at } d_1 = 2.6 \text{ miles for beam A}$$

$$h_\ell = 8996 \text{ ft}$$

$$\simeq 193\, H_1 \quad , \text{ at } d_1 = 2.0 \text{ miles for beam B}$$

Thus, the offending WTs being at large distances (compared to the first Fresnel distance) from the link paths, it appears that the Sky Valley earth station performance would be unaffected by the windfarm using any of the three types of WTs. For a windfarm of MOD-2 machines it can be shown that

$$\Gamma_T \sim 0.2 \times 10^{-2} \quad (-54 \text{ dB}) \text{ for beam A}$$

$$\Gamma_T \sim 0.3 \times 10^{-2} \quad (-50 \text{ dB}) \text{ for beam B}$$

In both cases, Γ_T satisfies the acceptability criterion (6).

No offending WT-sites have been identified for the Vallejo earth station whose performance would therefore be unaffected by the windfarm.

4.4 Interference to Television Reception

Interference effects to television reception or TVI effects produced by the windfarm have been assessed for Cordelia, Vallejo, Benicia, and for Regions A, B, C and D shown in Fig. 4 which also indicates the directions of all possible available TV signals in the area originating from Sacramento (SAC), San Jose (SJ) and San Francisco (SF). Specific information regarding the TV transmitters located in these three cities may be obtained from Tables 2.1 through 2.3.

Although the assessment has been carried out on the assumption that all of the TV signals listed in Tables 2.1 through 2.3 are available for reception at all the regions under consideration, it should be mentioned that due to the hilly nature of the terrain it is quite possible that some or all of the TV Channel signals from a particular city may be very weak (extremely poor reception) or unavailable in the region under study.

Quantitative analysis of WT-produced TVI effects at a site requires the knowledge of ambient signal strengths at the receiving and WT sites and the characteristics of the receiving antenna. The first two items of information are best obtained from measurements. In the absence of such measurements, we have made some approximations (Appendix III) to these quantities based on our previous experience [6].

Generally, for each assessed region, m_T values appropriate for reception of the highest and lowest TV Channel signals originating from each city are first calculated for a windfarm of MOD-2 machines which have the largest equivalent scattering areas (see Table 2.7). m_T values corresponding to MOD-5A and WTS-4 are then obtained, if required. The method of calculating m_T and a sample calculation are described in Appendix III. In the following sections we present the calculated m_T values for various regions from which the resultant TVI effects of the windfarm are assessed according to the criteria given in Section 3.4. Missing m_T values for any region indicate that assessment could be performed without further calculation or no adverse effects are anticipated. m_T values given and, hence, the assessment of interference effects, assume the use of a typical directional receiving antenna; for an isotropic (or poor) antenna m_T values are unchanged for forward region effects, and should be increased by 6 (≈ 1/0.18) and the assessment modified accordingly for backward region effects.

4.4.1 TVI Effects at Cordelia. Detailed calculations for this case are given in Appendix III. Table 4.6, prepared from the results discussed in the appendix, show the m_T values appropriate for the assessment of TVI effects on the TV reception at Cordelia. From the results shown in Table 4.6 the following assessment of TVI effects at Cordelia are made:

Nature of Reception	TVI Effects
C → SF	Unacceptable with MOD-2 on some Channels Marginally acceptable with MOD-5A Acceptable with WTS-4
C → SAC	Acceptable with MOD-2, MOD-5A or WTS-4
C → SJ	Acceptable on Channels 11 and 36 and marginally acceptable on Channel 54 with MOD-2 Acceptable with MOD-5A or WTS-4

Table 4.6

m_T Values for TVI Effects at Cordelia

WT Type	C → SF		C → SAC		C → SJ	
	$m_T \times 10^2$		$m_T \times 10^2$		$m_T \times 10^2$	
	Channel 44	Channel 2	Channel 40	Channel 3	Channel 54	Channel 11
MOD-2	15	49	9	9	30	10
MOD-5A	11	35	<9	<9	21	7
WTS-4	3	9	<9	<9	6	2

C → SF   Cordelia receiving signals from San Francisco

C → SAC   " " " " Sacramento

C → SJ   " " " " San Jose

4.4.2 TVI Effects at Vallejo. Receiving signals from San Francisco or San Jose: Windfarm is in the backward region and the m_T values are approximately 1/6 of the corresponding values for SF and SJ given in Table 4.6. Hence TVI effects would be insignificant with MOD-2, MOD-5A or WTS-4.

Receiving signals from Sacramento: This case is similar to Cordelia receiving signals from San Francisco. Therefore, the assessment is similar to that of C → SF given in Section 4.4.1.

4.4.3 TVI Effects at Benicia. For reception of all available TV signals the windfarm is in the backward region. No unacceptable TVI effects are expected with any of the three types of machines.

4.4.4 TVI Effects at A,B,C and D. The four areas, indicated in Fig. 4, are representative of the residential homes in the immediate vicinity of the windfarm. m_T values appropriate for reception of various TV Channel signals in each of these areas have been calculated after identifying the offending turbine sites. The results are shown in Tables 4.7 through 4.10. In each set of results under each column it is marked whether the offending turbine sites are in the backward or forward region discussed earlier; the number of sites contributing significantly is also indicated for each case.

Using the criteria given in Section 3.4, the TVI effects at A,B,C and D can now be assessed on the basis of the results given in Tables 4.7 through 4.10. As can be seen from Eqs. (7) and (8), the TVI effects caused by WTs in the forward region depend on the

Table 4.7

m_T Values for TVI Effects at A

WT Type	A → SF $m_T \times 10^2$ Channel 44	Channel 2	A → SAC $m_T \times 10^2$ Channel 40	Channel 3	A → SJ $m_T \times 10^2$ Channel 54	Channel 11
MOD-2	8	16	57	52	32	8
MOD-5A	6	11	41	37	23	6
WTS-4	1	2	11	10	13	3
	Backward Region N = 61		Forward Region N = 49		Mixed N = 6 forward N = 61 backward	

Table 4.8

m_T Values for TVI Effects at B

WT Type	B → SF $m_T \times 10^2$ Channel 44	Channel 2	B → SAC $m_T \times 10^2$ Channel 40	Channel 3	B → SJ $m_T \times 10^2$ Channel 54	Channel 11
MOD-2	7	11	30	52	8	11
MOD-5A	5	8	28	48	6	8
WTS-4	4	4	6	10	5	7
	Backward Region N = 67		Forward Region N = 40		Backward Region N = 67	

Table 4.9

m_T Values for TVI Effects at C

WT Type	C → SF		C → SAC		C SJ	
	$m_T \times 10^2$		$m_T \times 10^2$		$m_T \times 10$	
	Channel 44	Channel 2	Channel 40	Channel 3	Channel 54	Channel 11
MOD-2	3	4	3	4	3	4
MOD-5A	2	3	2	3	2	3
WTS-4*	54	5	54	5	54	5
	Backward Region N = 67		Backward Region N = 67		Backward Region N = 67	

*Large values are due to the coning effects of the blades.

Table 4.10

m_T Values for TVI Effects at D

	D → SF		D → SAC		D → SJ	
	$m_T \times 10^2$		$m_T \times 10^2$		$m_T \times 10^2$	
	Channel 44	Channel 2	Channel 40	Channel 3	Channel 54	Channel 11
MOD-2	25	6	3	>75	15	18
MOD-5A	18	5	2	>75	11	13
WTS-4	8	11	1	4	8	21
	Forward Region N = 51		Backward Region N = 67		Forward Region N = 25	

ambient signal strengths. Local terrain effects indicate that the ambient signal strengths in the region A,B,C and D would be weak, (this is consistent with other assumptions of $E_B/E_R = 10$) and we shall use the single criterion given by Eq. (7) to assess both forward and backward region TVI effects. With a properly oriented directional receiving antenna (having side and/or back lobe level of -15 dB, i.e., F(BT) = 0.18 in Eq. (III.1) unacceptable TVI effects at each site may be identified for each reception whenever the corresponding number appearing in the appropriate table is larger than 15. It can be seen from the results given in Tables 4.7 through 4.10 that no site is completely immune to unacceptable TVI effects (on all TV Channels) caused by the windfarm of MOD-2, MOD-5A or WTS-4; the forward region effects are generally found to be more severe. It should be mentioned that with a poor receiving antenna (F(BT) = 1 for both forward and backward regions), or an improperly oriented directional antenna, the backward region interference effects would be aggravated (for example, m_T values increased by a factor of 6 with a poor antenna) and hence, unacceptable TVI effects would occur at all sites on almost all TV Channels for all three machines. Although the interference effects at sites located within the windfarm have not been assessed, the results given here indicate that the TVI effects at such sites, on most of the available TV Channels, would be generally unacceptable. More detailed quantitative studies would be necessary to quantify the TVI effects and, hence, the amount of video distortion observed in specific cases.

4.5 TVI Effects at the CATV Head-End

A CATV Head-end, identified as CATV in Figs. 3 and 4, is located on top of Sulphur Spring Mountain (Fig. 2) at an elevation of about 955 ft above sea level. Assuming that the CATV antennas are mounted on top of a 45 ft tower, the elevation of all CATV antennas is 1000 ft.

It is assumed that the CATV Head-end receives all TV signals originating from SF, SAC and SJ. During reception of signals from SF and SJ, all WT sites are located in the backward region. For reception of signals from SAC, three turbine sites Nos. 6, 7 and 9 are located in the forward region and the remaining 64 are in the backward region; the three forward region turbines would produce insignificant interference effects and, hence, their effects are neglected. We shall therefore determine the interference signals assuming all offending turbine sites to be in the backward region.

In the present case, it is reasonable to assume that the ambient TV signals at the CATV head-end and at the WT sites are of the same order of magnitude, i.e., $E_B/E_R = 1$. For the purpose of calculation of m_T it is assumed that the CATV antenna beam is directed to receive maximum signals from the desired direction, and that the side and/or back lobe level of the antenna is -20 dB (i.e., F(BT) = 0.1). Calculated m_T values appropriate for the three types of machines and for the highest and lowest TV Channel signals originating from the three cities are shown in Table 4.11.

Table 4.11

m_T Values for TVI Effects at the CATV Head-End

WT Type	CATV → SF		CATV → SAC		CATV → SJ	
	$m_T \times 10^2$		$m_T \times 10^2$		$m_T \times 10^2$	
	Channel 44	Channel 2	Channel 40	Channel 3	Channel 54	Channel 11
MOD-2	6.6	1.2	6.2	1.3	7.2	4.1
MOD-5A	4.7	0.9	4.4	0.9	5.2	2.9
WTS-4	1.3	0.2	1.2	0.3	2.8	0.8
	Backward Region N = 67		Backward Region N = 64		Backward Region N = 67	

Note: TVI effects acceptable for $m_T \lesssim 5.0 \times 10^{-2}$

Under the assumption that acceptable TVI effects would occur for $m_T \lesssim 5 \times 10^{-2}$, the results of Table 4.11 indicate that the interference effects produced by the windfarm on the performance of the CATV Head-end would be:

(i) unacceptable on the highest Channels only for MOD-2.

(ii) unacceptable on Channel 54 (originating from SJ) for MOD-5A.

(iii) acceptable on all Channels for WTS-4.

5. Conclusions

The fundamental parameter required to estimate the electromagnetic interference effects of a WT is the equivalent scattering area of its blade. To the best of our knowledge, such information about the candidate WTs for the Solano Windfarm is not at present precisely known. We have obtained, only approximately, the required information by applying extrapolation and scaling laws to our present knowledge of the scattering areas of MOD-0A and MOD-1 WTs. It is therefore recommended that the more precise blade scattering area of each proposed WT be obtained, for example, by laboratory scale model measurements.

The TVI effects at a receiving site also depend quite strongly on the ratio of ambient signal strengths at the receiving and WT sites. In a rugged terrain like the Solano Windfarm it is difficult to determine these signal strengths theoretically. Although we have made approximations to these parameters based on our experience, the actual signal ratios may be different. For more precise TVI assessment, the desired ambient signal strengths should be measured at the receiving and WT sites.

APPENDIX I. CALCULATION OF Γ_T FOR ASSESSMENT OF VOR INTERFERENCE

It is assumed that the WTs of the farm may cause interference only if they are visible from the antenna of the VOR ground station, i.e., when the antenna and the WT(s) are within the radio line-of-sight distance. The radio line-of-sight distance (d_H) between two points at heights h_1 and h_2 above a smooth spherical earth is

$$d_H = \sqrt{2}\,(\sqrt{h_1} + \sqrt{h_2}) \quad , \qquad (I.1)$$

where d_H is expressed in miles and h_1, h_2 are in feet. Identifying h_1 as the VOR antenna height and h_2 as the WT height and assuming smooth terrain between the VOR station and the WT, Eq. (I.1) can be used to determine whether the WTs in the farm would be visible from the VOR antenna.

For example, in the case of Concord VOR station h_1 = 15 feet. Let the average height of a WT in the farm be h_2 = 625 feet. Thus from Eq. (I.1)

$$d_H \simeq 41 \text{ miles (66 km)} \quad .$$

Under the assumption that the terrain between the Concord VOR station (9 miles from the windfarm) and the windfarm is smooth, it appears that all the WTs in the farm would be visible from the VOR station.

This would be the worst case; local terrain may make some WTs invisible, however we shall not take that into account.

All of the visible WTs will not contribute equally to the interference produced in a given azimuth direction from the VOR station. Generally, WTs located along a radial direction (from the VOR station) may produce maximum siting errors (due to interference in azimuth direction perpedicular to that radial [3]. We thus divide the windfarm into radial sectors of width $\phi_o \pm 5°$, and count the number of WTs within 10-degree sectors centered on ϕ_o, as sketched in Fig. I.1.

Figure I.2 shows the ten-degree sectors of the windfarm appropriate for the Concord VOR. Relevant information about the offending wind turbines for the Concord VOR are shown in Table I.1 where we have also indicated the number of those turbines and their distances from the VOR which are nearest and farthest in that sector, from the VOR station. It is found from Table I.1 that the -40° sector contains maximum number of offending WTs. For simplicity of calculation we now assume that the turbines within this sector are located at an average distance

$$d = 52{,}000 \text{ ft} = 15.9 \text{ km} \quad .$$

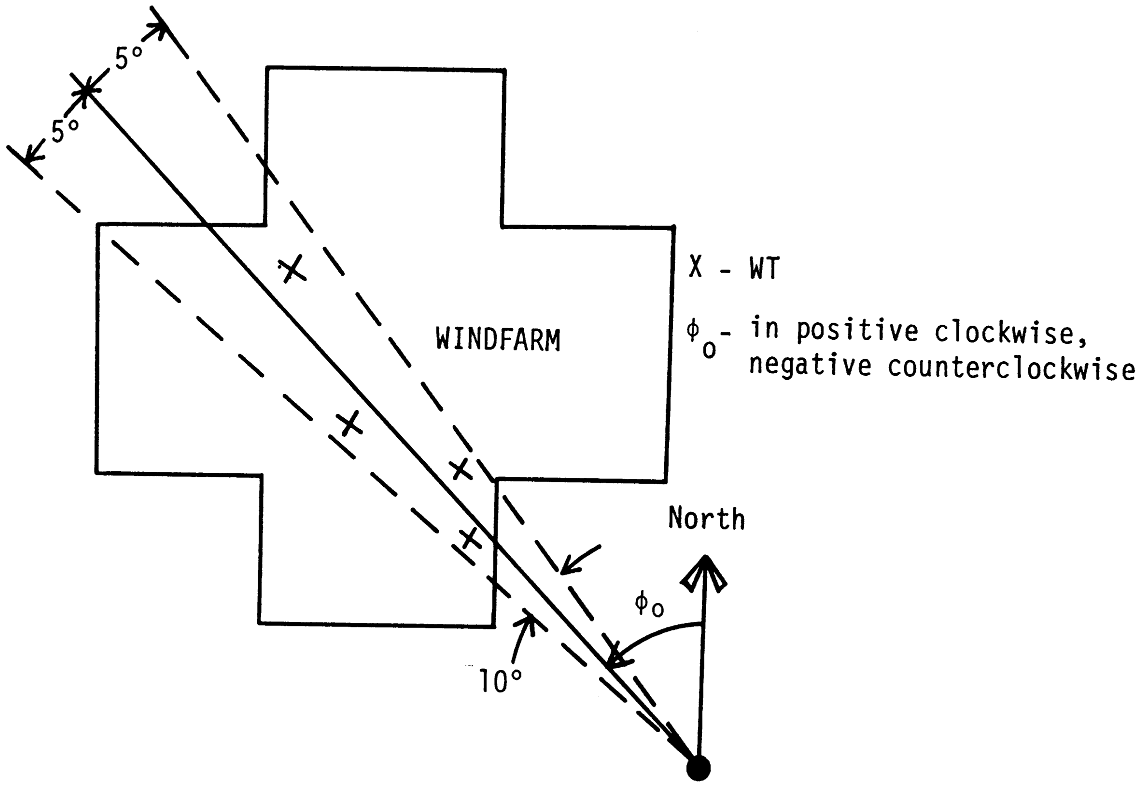


Fig. I.1 A Ten-Degree Sector of the Windfarm Centered on ϕ_o.

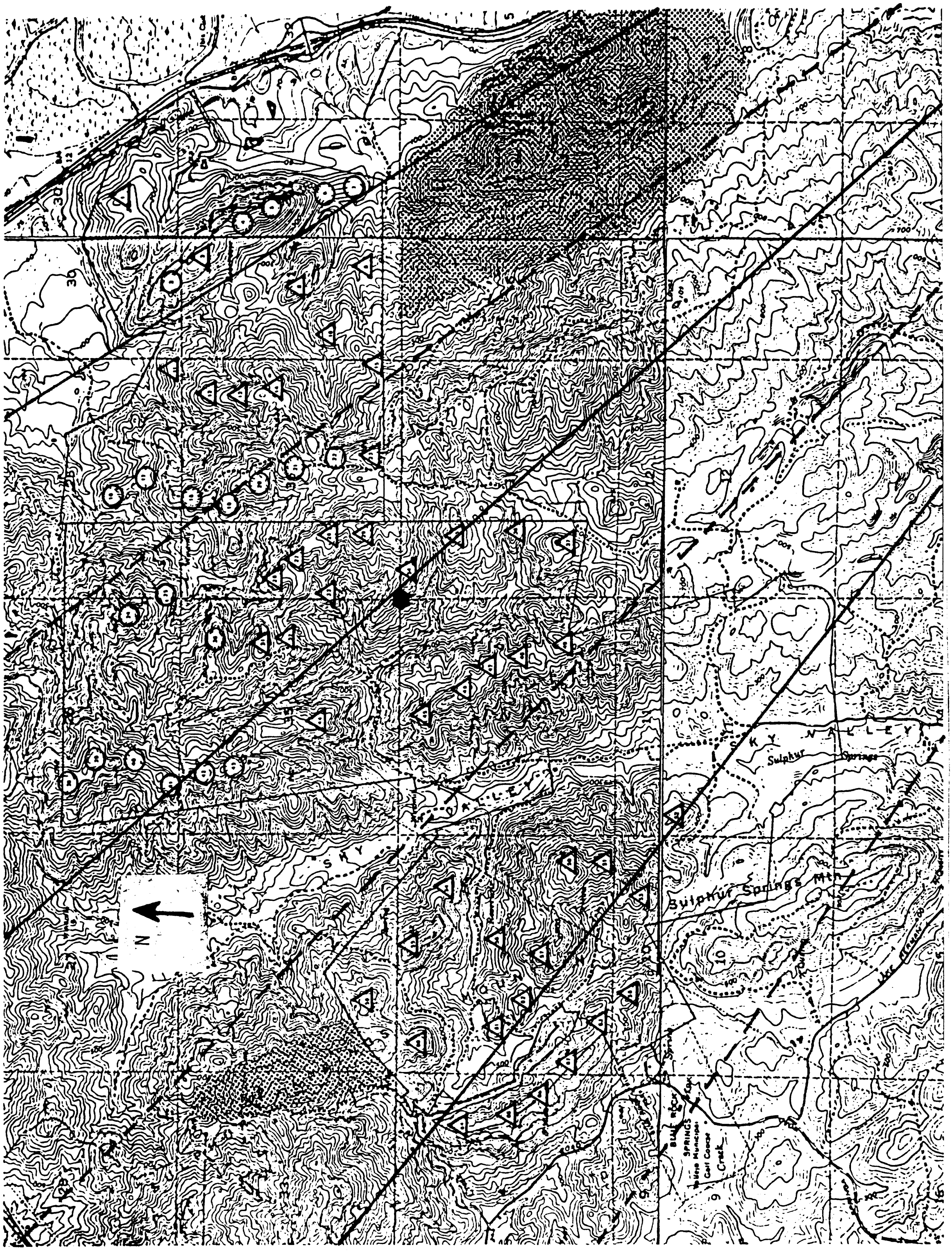


Fig. I.2 Diagram showing the offending WTs for the Concord VOR.

Table I.1

Offending WTs Within Ten-Degree Sectors of ϕ_o from the Concord VOR

ϕ_o	N	Nearest WT		Farthest WT	
		WT No.	Distance d	WT No.	Distance d
-30°	19	7	48,000	1	51,600
-40°	30	37	45,000	38	59,000
-50°	19	52	46,000	64	54,200

N : number of WTs

d : distance in feet from the VOR station

Assuming MOD-2 WT, Γ_T for 30 WTs are obtained as follows:

$$f = 120 \text{ MHz} \quad , \quad \lambda = 2.5 \text{ m}$$

for MOD-2 $A_e = 140 \text{ m}^2$

for one WT at a distance of 15.9 km

$$\Gamma \simeq \frac{2A_e}{\lambda d} = 7.04 \times 10^{-3} \ (-43 \text{ dB})$$

for 30 machines

$$\Gamma_T = \sqrt{30}\,\Gamma = 3.86 \times 10^{-2} \ (-28.3 \text{ dB})$$

To obtain Γ_T for the Travis AFB VOR, we assume that all 63 WTs contribute to the interference effects and that $d \simeq 19.3$ km and obtain for MOD-2 machines

$$\Gamma \simeq 5.80 \times 10^{-2} \quad (-44.7 \text{ dB})$$

$$\Gamma_T \simeq 4.57 \times 10^{-2} \quad (-26.8 \text{ dB})$$

For other machines, the desired values of Γ_T are obtained by using the appropriate values for A (Table 2.7).

APPENDIX II. ASSESSMENT OF INTERFERENCE TO MICROWAVE LINKS

We shall illustrate the assessment of windfarm interference to microwave links by describing the calculation procedure followed in a typical case. For a given WT site of elevation H_s, located at a horizontal distance r from the link path of elevation h_ℓ at the location of the WT, we define the following two parameters:

horizontal clearance $\Delta r = r - D/2$,

vertical clearance $\Delta H = h_\ell - h_T$,

where D = the rotor diameter of the WT and

$h_T = H_s + h_{WT} + D/2$, h_{WT} being the hub height of the WT.

The acceptability criterion for the site, based on the considerations of Fresnel distance (Section 3.2), is now

$$(\Delta H + D/2)^2 + r^2 \geq (3H_1 + D/2)^2 \quad , \qquad \text{(II.1)}$$

where H_1 is the first Fresnel distance (Fig. 8). Under limiting conditions, we now obtain from (II.1) the following acceptability criterion:

$$\begin{matrix} |\Delta H| \\ \text{or} \\ |\Delta r| \end{matrix} \gtrsim 3H_1 \quad , \qquad \text{(II.2)}$$

where

$$H_1 = \left[\frac{\lambda(d - d_1)d_1}{d}\right]^{1/2}, \qquad \text{(II.3)}$$

λ being the wavelength and d, d_1 as explained in Fig. 8.

Figure II.1 shows the microwave link paths superposed on the windfarm. For each link the offending sites (generally for $r_1 < 3H_1$) are identified, and the corresponding ΔH, Δr and H_1 are calculated for a given WT by using (II.2) and (II.3). For simplicity of calculation we shall assume that the windfarm is located at the center of the overhead paths (Nos. 27, 8 and 7 in Fig. II.1).

Sample Calculation for Path 28CC

From the data given in Table 2.5, we prepare the elevation diagram, shown in Fig. II.2, for the link Path 28CC whose one head-end (antenna No. 2) is located near the windfarm (Fig. II.1). It is assumed that $f = 10$ GHz, $\lambda \simeq 0.1$ ft, with MOD-5A ($h_{WT} = 250$ ft, $D/2 = 200$ ft) at each of the offending sites near path 28CC, and the various parameters required for the calculation of ΔH and Δr are now obtained by using Figs. II.1 and II.2. The results are shown in Table II.1.

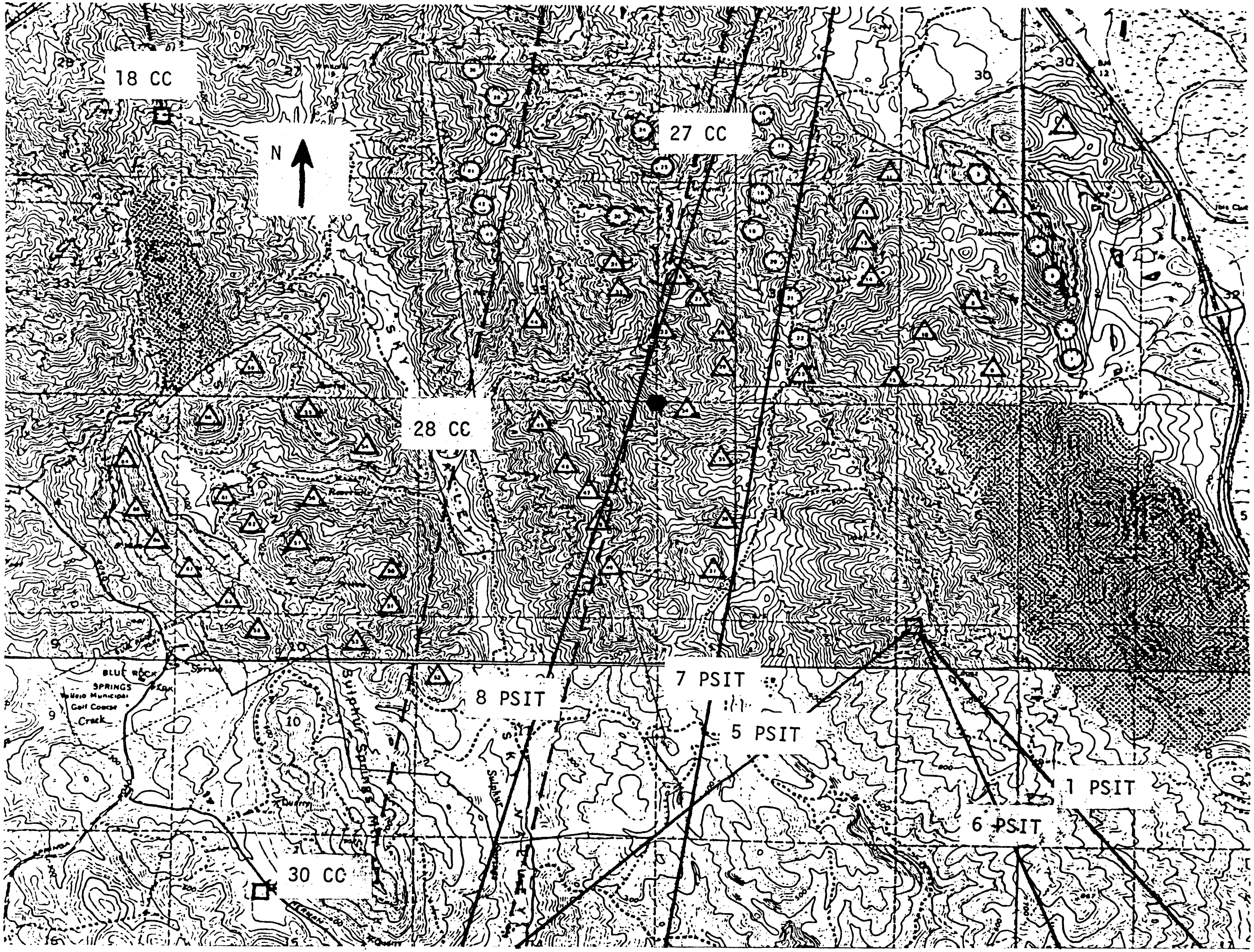


Fig. II.1 Microwave link paths above the windfarm.

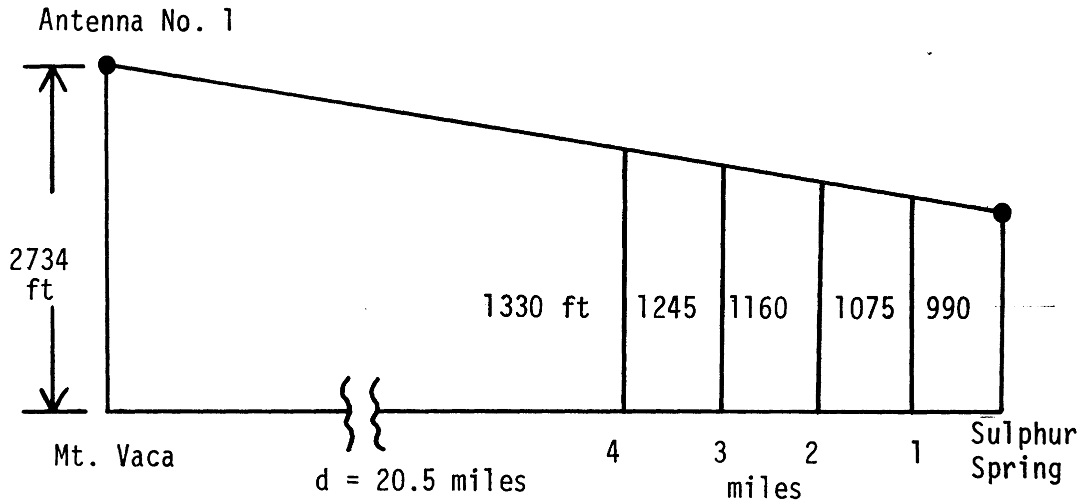


Fig. II.2 Elevation Diagram for Link Path 28CC.

Table II.1

MOD-5A Windfarm Interference Assessment Parameters for Link Path 28CC

Site No.	h_T (ft)	r (ft)	Δr (ft)	ΔH (ft)	d_1 (miles)	$3H_1$ (ft)
39	1530	750	550	-242	3.5	117
40	1430	720	520	-185	3.3	114
41	1410	720	520	-158	3.2	112
42	1367	480	280	-122	3.0	111
43	1310	250	50	- 98	2.8	108

All sites except 43 satisfy the acceptability criterion (II.2). It can also be shown that with MOD-5A and WTS-4 a similar conclusion holds.

During the assessment of interference to various links we shall use the acceptability criterion $\Delta H \geq 3H_1$ if $\Delta r < 3H_1$ and $\Delta r \geq 3H_1$ if $\Delta H < 3H_1$.

APPENDIX III. CALCULATION OF TVI EFFECTS

III.1 Method

The amplitude modulation index (m) of the received signal at a site caused by the rotation of the blades of a WT is calculated by using the following approximate relationship [6]:

$$m = \frac{2A_e}{\lambda d} \frac{E_B}{E_R} F(BT) \frac{\sin \left(\frac{\pi L_e}{\lambda} \sin \alpha \right)}{\frac{\pi L_e}{\lambda} \sin \alpha} , \qquad \text{(III.1)}$$

where A_e = equivalent scattering area of the blade,

L_e = equivalent length of the blade,

d = distance between the receiving point R and the phase center B of the WT blade,

E_B, E_R = amplitudes of the ambient electric fields at B and R, respectively,

$F(BT)$ = antenna discrimination factor and

α = the elevation angle of B as seen from R for MOD-2A or MOD-5A, and should be changed to (α - 6°) for WTS-4.

Equation (III.1) assumes that the receiving antenna is properly oriented to receive the maximum signal from the transmitter T, i.e., the antenna beam is directed in the direction of T. Under this condition, for turbines located within the forward region of the antenna, defined as the region within ±30 degrees of the mainbeam of the antenna, F(BT) = 1; for turbines located in the backward region (i.e., outside the forward region) the antenna provides discrimination against the interfering signals caused by the WTs and F(BT) = side or back lobe ratio of the antenna. The following assumptions have been made in all of our calculations: (a) F(BT) = 1 for turbines in the forward region, F(BT) = 0.18 (-15 dB) for turbines in the backward region; (b) E_B/E_R = 10.0 (20 dB), an assumption based on our previous work [6].

For a given transmitter the following procedure is followed during calculations for a site R:

(i) identify the turbine nearest R, whether in the forward or backward region,

(ii) determine d,α and

(iii) obtain m using (III.1).

If m obtained in (iii) is less than the value given by Eq. (7) Eq. (8) then,

(iv) identify the offending turbines N within the forward or backward region,

(v) establish an average distance d_{av} and elevation angle α_{av} for the offending turbines and obtain m_{av} using (III.1) and

(vi) judge acceptability by comparing with Eq. (7) or Eq. (8).

As an illustration, we show in the following section the calculations for the TVI effects at Cordelia.

III.2 Sample Calculations for TVI Effects at Cordelia

Receiving TV Signals from San Francisco (SF). From the nature of the terrain it appears that all signals from SF may not be available for satisfactory reception at Cordelia. We shall show the calculations for Channel 44 (λ = 1.5 ft) and Channel 2 (λ = 16.5 ft) and assume the use of MOD-2 WTs, i.e., A_e = 1507 ft^2, L_e = 207 ft.

Most of the turbines are in the forward region (see Fig. 4). Consult Figs. 2 and 4, and identify WT at site 16 as the nearest turbine.

For WT 16, d = 3.25 miles, $\alpha \simeq$ 0.84 degrees. Thus with E_B/E_R = 10, F(BT) = 1. Obtain from (II.1):

$$m = 2.3 \times 10^{-2} \quad \text{for Channel 44}$$

$$= 1.0 \times 10^{-2} \quad \text{for Channel 2}$$

The above indicates that the TVI effects of the nearest turbine are acceptable for all Channels from SF.

The entire windfarm is in the forward region, i.e., N = 67. The average distance and elevation for the turbines is: d_{av} = 4.75 miles (in this case it is the distance of the windfarm center CF), α_{av} = 1.7 degrees.

$$m_{av} = 1.8 \times 10^{-2} \quad \text{for Channel 44}$$

$$= 6.0 \times 10^{-2} \quad \text{for Channel 2}$$

with N = 67,

$$m_T = 15 \times 10^{-2} \quad \text{for Channel 44}$$

$$= 49 \times 10^{-2} \quad \text{for Channel 2}$$

It appears that with MOD-2 windfarm the TVI effects on the reception some lower Channels would be unacceptable.

The corresponding m_T values for the other two machines are:

MOD-5A:

$$m_T = 11 \times 10^{-2} \quad \text{for Channel 44}$$

$$= 35 \times 10^{-2} \quad \text{for Channel 2}$$

WTS-4:

$$m_T = 3 \times 10^{-2} \quad \text{for Channel 44}$$

$$= 9 \times 10^{-2} \quad \text{for Channel 2}$$

With the MOD-5A or the WTS-4 the TVI effects of the windfarm would be <u>acceptable</u> on all Channels.

Receiving TV Signals from Sacramento

The entire windfarm is in the backward region. We shall show results for Channel 40 (λ = 1.6 ft) and Channel 3 (λ = 15.1 ft). Use d_{av} = 4.75 miles, α_{av} = 1.6 degrees, F(BT) = 0.18, E_B/E_R = 10 and N = 67. Calculations are similar and we only show the final results:

MOD-2:

m_T = 8.8×10^{-2} for both Channels 40 and 3

With the MOD-5A and the WTS-4, the m_T values would be lower than the above and, hence, are not shown. The TVI effects of the windfarm using any of the three types of WTs would be insignificant.

Receiving TV Signals from San Jose

About 25 WTs are in the forward region. We shall show results for Channel 11 (λ = 4.9 ft) and Channel 54 (λ = 1.4 ft). Use, d_{av} = 3.8 miles, α_{av} = 1.45 degrees, F(BT) = 1.0, E_B/E_R = 10. Ignoring the effects of the turbine in the backward region we obtain:

MOD-2:

m_T = 30×10^{-2} for Channel 54

= 10×10^{-2} for Channel 11

MOD-5A:

m_T = 21×10^{-2} for Channel 54

= 7×10^{-2} for Channel 11

WTS-4:

$$m_T = 6 \times 10^{-2} \qquad \text{for Channel 54}$$

$$= 2 \times 10^{-2} \qquad \text{for Channel 11}$$

With MOD-2, the TVI effects are acceptable on all of the Channels of interest except on Channel 54 where they are marginally acceptable. With the MOD-5A and the WTS-4, the TVI effects are acceptable on all of the Channels of interest.

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