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USE OF SATELLITES TO DETERMINE OPTIMUM LOCATIONS FOR SOLAR POWER STATIONS

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ABSTRACT

Ground measurements of solar radiation are too sparse to determine important mesoscale differences that can be of major significance in solar power station locations. Cloud images in the visual spectrum from the SMS/GOES geostationary satellites are used to determine the hourly distribution of sunshine on a mesoscale in the continental United States excluding Alaska. Cloud coverage and density as a function of time of day and season are considered through the use of digital data processing techniques. Low density cirrus clouds are less detrimental to solar energy collection than other types; and clouds in the morning and evening are less detrimental than those during midday hours of maximum insolation.

The seasonal geographic distributions of sunshine are converted to Langleys of solar radiation received at the earth's surface through the use of transform equations developed from long-term measurements of these two parameters at 18 widely distributed stations. The high correlation between measurements of sunshine and radiation makes this possible. The output product will be maps showing the geographic distribution of total solar radiation on the mesoscale which is received at the earth's surface during each season.

INTRODUCTION

Intermediate scale (mesoscale) differences in the distribution of solar radiation received at the earth's surface can be very important in selecting the location for a large solar energy station. Daily totals and in some cases hourly records of solar insolation exist for about 54 National Weather Service and 27 Cooperative stations in the 48 contiguous United States [1]. Generalized maps have been drawn by use of data from these stations, but they cannot depict the mesoscale differences. There are some excellent prospective power sites within areas that are mostly nominal quality, and there are some poor sites within areas that are generally high quality.

Since clouds of the "low-cloud family," including those of vertical development, tend to be thick and contain lots of moisture, they are the major absorbers or attenuators of incoming solar radiation. These low cloud types are most responsive to surface features such as localized heating or cooling, coastal effects, and topography. This responsiveness is manifest in the time, space, and density distributions of these low cloud types. These localized differences in the low-cloud family are the major cause of mesoscale differences in solar radiation reaching the earth.

There are two types of solar radiation measurements commonly made at the earth's surface, direct and total. Direct is that received directly from the sun and is measured on a flat surface normal to the sun's rays. The Eppley normal incidence pyrheliometer is a typical instrument used for this. Total radiation is the direct plus that reflected from all parts of the sky, and it is measured on a horizontal flat surface. The Eppley model II pyranometer is a typical instrument for this measurement. At many stations, daily totalizers are used on both types of instruments. At some stations, analog chart recorders are used so that the time distribution and hourly totals of radiation can be obtained [1]. Eighteen of the National Weather Service pyranometer stations that have analog chart recorders, which provide hourly radiation data, also have sunshine switches with recorders that provide minutes of sunshine per hour. The sunshine switches are calibrated to indicate sunshine so long as enough sunlight is present for nearby objects to cast a shadow. Thus periods with high thin clouds are recorded as sunshine. Depending upon the threshold of the switch, heavier clouds may also register as sunshine.

In this study, total solar radiation received per hour is correlated with minutes of sunshine per hour recorded at 18 surface stations in different climatic and air quality regions of the United States. The SMS/GOES geostationary satellites provide mesoscale images of cloud cover and conversely sunshine by hours of the day. The ground station relations between sunshine and total radiation are used to transform the satellite measurements of sunshine into equivalent solar radiation data. Computer processing of the data provides seasonal mapping of sunshine and solar radiation on the mesoscale [2]. Early research on the use of satellites to measure solar energy was conducted by Fritz, et al. [3]. More recent works relating to the subject include Thekaekara [4], Hanson [5], and Vonder Haar [6].

In addition to cloudiness, latitude, season of the year, time of day, and air quality (turbidity, etc.) are important factors in solar insolation. Cloudiness with respect to time of day is important because morning and evening cloudiness is less detrimental than that at midday. This can be particularly important if a high temperature solar concentrator is to be used, in which case, the midday high energy hours of sunshine would be most valuable. The geostationary satellite observations throughout the day provide these hourly distributions of cloudiness and sunshine.

Our ground station data used to write the transforms from sunshine to solar radiation are from 18 stations throughout the United States. For example, Great Falls, Montana, data will be applied to the northern high plains and data for Boston, Mass., will be used to develop transform relations for the northeastern seaboard. This system will automatically compensate for differences in air quality in our results because each station will be fairly representative of its region.

DATA SOURCES

Daytime satellite imagery from the Stationary Meteorological Satellite (SMS-1) is being used to provide cloud data for 1975. The bulk of the data will be from the visual channel (.55-.75μ) of SMS-1 located at 75°W longitude over the equator; but in order to adequately cover the western portions of the country later in the afternoon, it will be necessary to either use output from SMS-2 (at 115°W longitude for most of the year) or from the infrared channels of SMS-1. Since SMS-2 was drifted westward to 135°W longitude during the fall of 1975, and 10" x 10" photos are being read, the reduction of data will be extremely complex if its use becomes necessary. It is therefore presently planned to use only data from SMS-1 if possible. Figure 1 shows the areas of coverage of SMS-1 and -2.

The satellite imagery will be compared with solar radiation and sunshine data from the 18 stations shown in Figure 2. These were chosen because they had relatively long and reliable hourly records of simultaneous radiation and sunshine duration from the same locations. Most of the stations have information for each hour of the day for the five years 1952-1957. This is contained on magnetic tape compiled from records at the National Weather Records Center.

While many others have looked at the relationship between the two variables for one or two stations, (see [7] for a summary of such work) the broader coverage of this project requires that we establish such relationships for more stations representative of the various latitudinal and climatological regions of the U.S.A.

DATA ANALYSIS

A correlation analysis is being made on the five years of hourly sunshine and hourly solar radiation data for the 18 continental U.S. stations. The taped information has been grouped into monthly averages of each variable after classification by pairs of hours of the day, i.e., the two middle-hour values are considered as one, as are the earliest and latest, etc. using local solar time. These monthly values are then combined into seasonal values for the five years July 1952-June 1957 which are plotted for each station. In this way the data are still amenable to checking for accuracy, yet handled manually easily enough to reveal both the relationships between insolation and duration of sunshine for a given station as well as the differences which may exist between stations.

The aim of that portion of work is to determine whether one relatively simple relationship can be used for all continental U.S. locations for a given season. The complexity of the final computer analysis of the SMS-1 photographs will rise by nearly an order of magnitude if many areas are quite different from each other.

Figure 3 shows a typical gridded cloud photograph. The portion used to cover the U.S. is a small part of a 10" x 10" photograph which covers about one-fourth of the full disk image. The SMS-1 satellite spins at 100 revolutions per minute. The VISSR's scanning mirror faces the earth for about one-twentieth of each complete 360-degree rotation, scanning from west to east in eight identical visible channels and two redundant IR channels. The scan data is immediately transmitted in digital form to the Wallops Island, Va., Command and Data Acquisition station (CDA). While the spacecraft is completing its revolution, the mirror moves to the next southward step and scans again when it is looking at the earth once more.

Within 18.2 minutes the radiometer accomplishes the 1821 scan steps required to provide an image of the coverage area, Figure 1. The resulting visible images, made only in daylight, contain 14,568 lines and have a resolution of nearly 1/2-mile at the nadir point. IR images, acquired in darkness as well as in daylight, [illegible] have a total of 1821 lines, with 5-mile resolution. Allowing time for the scanning mirror to return to its starting point, and for correction of any "wobble" which may be caused by this retracting action, the Satellite Service scheduled GOES picture coverage at 30-minute intervals. That picture rate provided far more data each day than necessary for our studies.

At the CDA station, the eight lines of visible data acquired while the spacecraft looks earthward are gridded automatically and the rate of data transmission reduced, "stretched." As the satellite is completing its revolution and the VISSR is looking toward space, the stretched visible data signals are retransmitted from the CDA station through the satellite to the NESS at Federal Office Building number 4 in Suitland, Maryland and then relayed by microwave to the NESS Central Facility a few miles away.

Portions, such as those marked in Figure 3 of the analog grey scale 10" x 10" photographs received from NOAA are being read on the television scanner of a GE Image-100 at NASA/KSC. This scanner produces 512 bits of information per line for 512 lines. The programmed output is a digital tape in ERTS format which will be processed on the University of Miami Univac 1106 computer. Three to five levels of cloud intensity will be used with an average space resolution on the order of 4-5 miles. The SMS VISSR imagery on our photographs has a basic resolution of one mile at the sub-point. This is degraded due to viewing angle about 18% at Miami to 1.18 miles and to about 3.77 miles at the far corner of the photograph near Seattle, Wash. Since the GE Image-100 will scan each photograph twice to cover the E-W U.S.A., but only once in the N-S direction, each of the 512 lines will correspond to about two of those on the photograph.

RELATIONS BETWEEN HOURS OF SUNSHINE AND SOLAR ENERGY

Figure 4 gives the annual mean daily solar radiation in Langleys (gram calories per square centimeter) based upon solar radiation measurements at a number of National Weather Service and cooperative observation stations in the United States [8]. The stations shown on this map do not represent the solar radiation data sources. Considering the fact that data from less than 85 stations in the 48 contiguous states were available, it is obvious that very much interpolation and extrapolation of the data was necessary to produce this map. Also, many of these stations have daily totalizers of radiation so that the hourly distribution of radiation cannot be determined from their past records. Relations exist between hourly radiation and hourly sunshine. Therefore, with good hourly sunshine and solar radiation data for only a few stations, the transform equations can be written to convert the vastly more detailed satellite data on hourly sunshine to equivalent Langleys of solar energy arriving at the earth's surface each hour.

Several factors enter into the relations between cloud free areas, or sunshine, as observed by the satellite and insolation received at the earth's surface. One important consideration is the time of day of maximum sunshine, whether morning and evening or midday. Two places with the same number of hours of sunshine per day can receive quite different amounts of solar energy depending upon this factor. Also, time of the year, station altitude, latitude, air pollution, and atmospheric moisture content are influential factors. Our derived relations between minutes of sunshine per hour and solar energy received are by hours of the day so that they can be used to convert the satellite measurements of sunshine to equivalent energy as a function of time of day. The 18 ground stations which we are using to develop these transform relations are widely dispersed so that they encompass different altitudes, latitudes, climates, and air quality. The relations derived for a particular station will be applied over the region around the station for which it is representative.

Many investigators have found good correlations between sushine and solar radiation received at a given place and time of year. However, most of them have compared daily total sunshine or percent of possible daily sunshine with the daily total radiation [7], [9], [10], [11], [12], [13]. Their results do not apply directly to our problem because they do not provide correlations between sunshine and radiation by hours of the day. They do provide a check on our results if we sum our hourly values of sunshine and radiation for all hours of the day.

Figures 5 and 6 are preliminary graphs of insolation versus minutes of sunshine per hour for pairs of morning and evening or midday hours at Madison, Wisconsin, for June and December. The hours are paired to give approximately equal sun angles fore and aft of noon true sun time (TST). These curves tend to show little seasonal change at the zero sunshine end of the scale because under such dense overcast conditions all of the energy received at the earth's surface is by the scatter mode. This is not affected greatly by the seasonal change in sun angle. Conversely, the clear sky or total sunshine end of the scale shows a much greater seasonal change because a large portion of the energy is direct and is sensitive to sun angle.

The sunshine switch used by the National Weather Service to measure minutes of sunshine per hour is biased. It is calibrated to register sunshine when a shadow is cast by nearby objects. This can occur with some degree of opaque clouds. At the other end of the scale, dense clouds must exist to register as zero sunshine. This means that a zero sunshine hour or day is truly cloudy, but a total sunshine hour or day may or may not be clear. Totally clear hours and days, particularly midday and in summer, should register slightly higher total insolation than is shown at the right in our curves.

Another graph similar to Figures 5 and 6 is being drawn for the combined spring and autumn relationship for Madison. The same seasonal graphs will be prepared for the other 17 stations shown in Figure 2. These will then be compared to determine how much, if any, the curves can be smoothed, and the geographical area over which each will be applied when converting cloudiness variables from the satellite photographs to insolation.

CONCLUSIONS

Ground measurements of solar radiation are too sparse to determine important mesoscale differences that can be of major significance in solar power station locations. A high positive correlation exists between recorded sunshine and solar energy received at a given place. Geostationary satellites can monitor sunshine (cloud free areas) throughout the day over large expanses of continents and oceans with great detail. Relationships can be derived between solar radiation and sunshine for different latitudes, seasons, and times of day by use of some existing records at a few stations. Computer techniques can apply these relationships to the satellite observations in order to obtain detailed maps of land and water areas showing the best possible locations for solar power stations.

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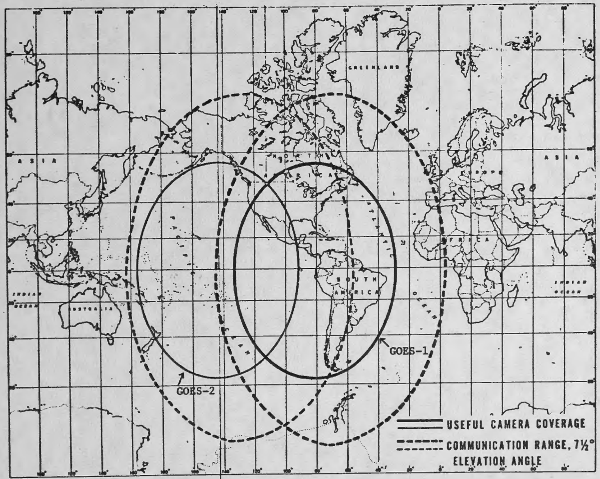

Figure 1. Typical coverage from a 2-GOES system showing area of useful camera coverage and communications range at 7.5-degree antenna elevation for data collection and relay.

HEMISPHERIC SOLAR RADIATION - HOURLY STATIONS

AND HOURLY SUNSHINE RECORDING STATIONS

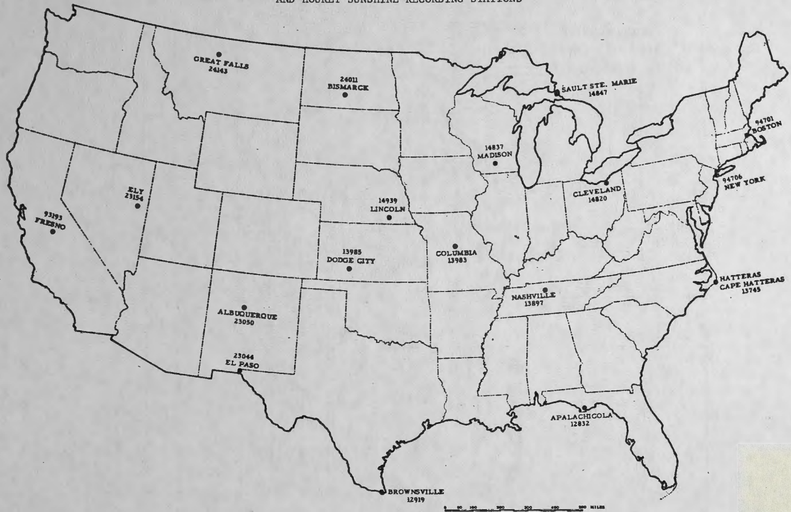

Figure 2

Figure 3. Visible Spectrum Image of Clouds Over the United States from SMS-1, Geostationary Satellite, 1800 GMT, 1 January 1975.