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COMPARING SATELLITE REMOTE SENSING AND GROUND NETWORK MEASUREMENTS FOR THE PRODUCTION OF SITE/TIME SPECIFIC IRRADIANCE DATA

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Abstract—In this article, we compare the accuracy of satellite-derived time/site specific hourly irradiances, with that of irradiances obtained via extrapolation and/or interpolation of nearby ground-measuring stations. A comprehensive study undertaken by the International Energy Agency [Zelenka *et al.* *Final Report of International Energy Agency Solar Heating and Cooling Program* (1992)] had addressed this question, but had limited its scope to daily total irradiances. The present study focuses on hourly data. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Site/time specific irradiance data are needed to simulate the output of solar energy systems (e.g. PV) in relation to other time/site specific quantities that are indirectly related to the solar resource (e.g. the load requirements of a utility, a substation or a building). Standard climatological data such as typical years, or climatologically representative stochastic data may be appropriate for system design or for energy production calculations, but they are not sufficient to study a system's interaction with its intended end-use if there is any relationship between the two.

The use of representative sites where irradiance data are measured or modeled has been a common practice for engineering calculations because of the scarcity of irradiance measuring stations. In the U.S.A., the National Solar Radiation Data Base (NSRDB, 1994) includes data for 239 locations which can be used to simulate systems throughout the country. However, whereas this practice may be acceptable for standard energy calculations, nearby site extrapolation may prove very inaccurate when site/time specific data are needed. Another source of irradiance data, remote sensing from geostationary satellites, though inherently less accurate than ground-based measurements, may be more suitable to generate site/time specific data at arbitrary locations and times.

2. EXPERIMENTAL DATA

2.1. *Ground-based solar radiation measurements*

The ground truth network considered in this paper includes 12 stations in south-eastern New York State and Massachusetts (see Fig. 1).

Ten of these stations—southern New York State and Massachusetts—were operated by Ascension Technology (ATI) on behalf of NYSERDA (1991–1995) and measured global, direct and diffuse irradiance with ATI-type rotating shadowband radiometers (RSR). One station located near the Albany Airport, operated by AWS Scientific on behalf of Niagara Mohawk Power Corporation (1990–1995) used a Michalsky-type RSR. The last station, located at the University at Albany (1991–1995), includes WMO first class measurements of global, direct and diffuse irradiance.

All data were carefully scrutinized through both automatic and visual quality control. In addition, instrument calibration throughout the network was verified and, if needed, corrected *a posteriori* on a monthly basis, to ensure consistency throughout the network. Calibration

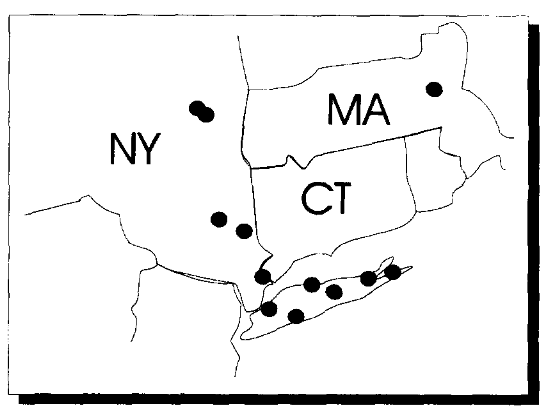

Fig. 1. Distribution of ground-truth stations.

verification was based on clearest-hours intercomparison of direct normal irradiance at all sites. The quality control and calibration control procedures have been described by Perez and Seals (1995).

2.2. Satellite data

The satellite data consist of intermediate resolution images from the visible channel of NOAA's geostationary weather satellite GOES 8. Ground resolution of these images in the considered region is of the order of 10 km latitude by 13 km longitude. Navigated images covering the north American continent and the Atlantic Ocean are distributed on an hourly basis trough the Internet Data Distribution System (1995). A portion of these images, covering the mid-Atlantic region of the US has been archived at our Center since May 1995 for research purposes. An example of the archived frames is shown in Fig. 2.

3. METHODS

3.1. Extrapolation

Nearest neighbor extrapolation constitutes the simplest method of estimating radiation at a given point from an existing measuring site. It is also the only ground-based method available when, as in most of the world, the density of ground stations is low.

For this study, we analyzed a total of 66 pairs of stations extracted from our 12-station network.

3.2. Interpolation

The interpolation scheme evaluated in this article is a weighted average gravity interpolation. The interpolated estimate is a weighted average of all surrounding sites within a given acceptance radius. The weights are a function of the square of the inverse distance from each station to the interpolated site (hence the term gravity). This interpolation method is deterministic, that is, the weights are assumed, *a priori*, to vary as a given function of the distance. More sophisticated interpolation methods such as kriging would reset the weighting scheme for each case, based on the current spatial structure of the radiation field (estimated from the network's stations). Gravity and other interpolation techniques are discussed in detail by Zelenka *et al.* (1992).

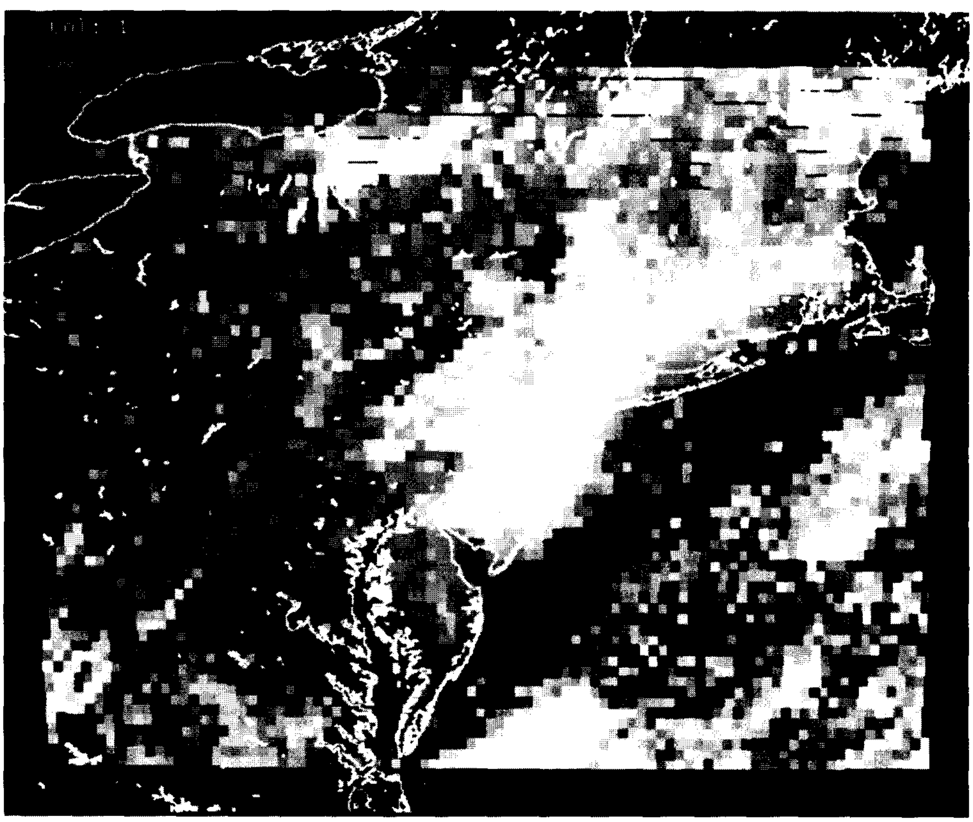

Fig. 2. Example of the northeastern US intermediate resolution visible frames from GOES-8 archived at our Research Center.

Interpolation accuracy is quantified in terms of RMSE by comparing each site's measurements to interpolated data from two or more of the other sites.

As a result of the limited number of sites and the non-ideal distribution of stations in the network, and in order to differentiate interpolation from extrapolation, we selected only a fraction of the possible interpolation combinations where the considered site would be reasonably well surrounded by the interpolating sites. A selection criterion based on the ratio between the average weighted interpolating distance D, and the average distance from considered site to the weighted barycenter of the interpolating sites X was used. Only combinations where D/X exceeded 1.75 were selected. The mathematical expressions of D and X are given below:

$$D = \sum_i d_i w_i$$

where d_i is the distance from each interpolating site to the considered site and w_i is the assigned weight of each interpolating site:

$$X = \left\{ \left[\sum_i (x_i - x) w_i \right]^2 + \left[\sum_i (y_i - y) w_i \right]^2 \right\}^{0.5}$$

where x, y, x_i and y_i are the Cartesian coordinates of the interpolated and each interpolating site respectively.

3.3. *Satellite image-to-ground irradiance conversion*

Satellite conversion algorithms are generally categorized into statistical or semi-empirical models and physical models. The former make use of the well known observation that atmospheric transmittance is linearly related to the planetary albedo (e.g. see Schmetz, 1989) sensed by the satellite. The latter infer surface irradiance via physical simulation of radiation transfer through the atmosphere, sometimes using additional satellite-measurements such as IR and atmospheric water content (e.g. see Gautier *et al.*, 1980; Pinker and Ewing, 1985).

Differences in performance between the two types of models have not been observed to be large (e.g. Schmetz, 1989; Whitlock *et al.*, 1990) because the primary source of model imprecision, the effect of cloud patterns, cannot be rigorously modeled. The known advantage of physical models resides in the fact that they can operate without some local tuning which is required by statistical models, at least given the current developmental stage of the latter.

For this study, we consider a simple statistical satellite-to-ground irradiance model developed by Zelenka (1995), after Moussu *et al.* (1989), and Schmetz (1989). Although we suspect that the choice of model is far from critical, it is briefly described.

The model includes two basic steps.

The first step is to normalize all satellite pixels to a common solar position. The normalization function used is the optical air mass. In addition, since the model had been developed to work with METEOSAT featuring a linear-response visible sensor, an additional normalization was necessary here to account for the non-linear (quadratic) response of the GOES-8 visible sensor.

The second step is to relate the dynamic range of the normalized pixels to a simple clear sky global irradiance model. For a given pixel, the satellite-derived irradiance is a fraction of the modeled clear sky irradiance, depending on its normalized value—i.e. the darkest pixels at a given site correspond to clear sky conditions, while the brightest pixels correspond to heavy cloud conditions. Irradiances for heaviest cloud conditions are arbitrarily set at 2% of the clear sky values. Of course, the dynamic range is site (and time) dependent because the darkest pixels depend on the local ground albedo which tends to evolve over time and space (vegetation change, snow cover, etc.). At this stage of model implementation no attempt was made to account for evolving ground albedo. However, the model was "tuned" to Albany measurements in order to remove its overall bias. We expect to minimize the importance of this tuning as we further the implementation of the model and fully evaluate the behavior of the selected clear sky model for the region of interest.

The clear sky model is that developed by Kasten (1984) as an extension of the pyrheliometric formula (Kasten, 1980). This model may be adjusted locally and seasonally by modifying the Linke turbidity factor. For this investigation, we used climatologically representative averages of monthly Linke turbidity factors for the north-eastern US.

4. RESULTS

4.1. *Extrapolation*

In Fig. 3 we present the relative root mean square error of extrapolation plotted as a function of distance in a variogram-like fashion. Each point represents a pair of stations in the network. For information, a relative RMSE of

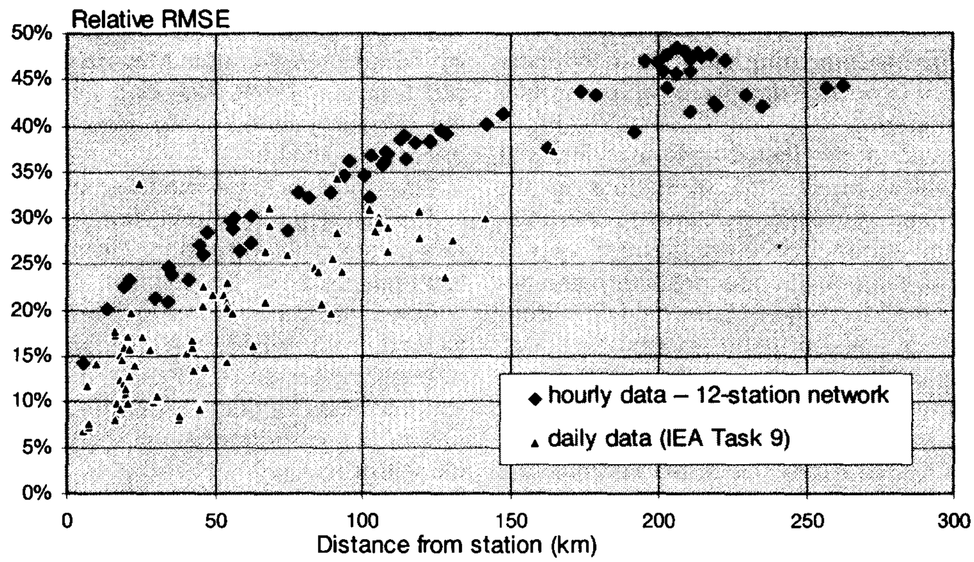

Fig. 3. Relative RMSE as a function of the station extrapolation distance.

25% represents about 90 Wm^{-2} in absolute terms.

- As expected RMSE is found to increase with distance, asymptotically tending toward a noise level where relationship between sites becomes random.
- The tightness of the trend is quite remarkable and indicates that the considered northeastern US region is quite homogeneous in terms of solar radiation field structure.
- A relatively large extrapolation error (15%) persists at very short distances (4 km). This phenomenon sometimes characterized as "nugget effect" is a result of the discontinuous nature of hourly radiation spatial structures (i.e. cloud-blue sky). Hence, extrapolation, even from a nearby site, may not be satisfactory when the time/site specificity of the data is critical.

In Fig. 3, we have also plotted extrapolation RMSEs for daily irradiances, reporting the results of IEA Task 9 (Zelenka *et al.*, 1992). The daily data points come from the analysis of six radiation networks in Germany, Switzerland, Sweden, the northeastern, northwestern and southwestern US. The trend observed by Zelenka *et al.* showed that degradation with distance was not strongly site dependent. It is however strongly time-step dependent as we notice a marked increase in RMSE from daily to hourly extrapolations, with almost a tripling of the nugget effect.

4.2. *Interpolation*

RMSEs obtained for interpolation are plotted in Fig. 4 as a function of the distance from the closest interpolating site. Also plotted, for comparative purposes, are extrapolation RMSEs presented above.

A small but noticeable improvement over extrapolation is apparent as distance increases. RMSE at short distances remains basically unchanged for short station distances.

This observation is probably a result of the fact that, in relation to extrapolation, interpolation is a more efficient detector of large atmospheric patterns (e.g. passage of fronts) than of small scale cloud structures.

4.3. *Satellite*

Satellite global irradiance estimates obtained for the closest pixel to Albany from May 1995 to January 1996 were compared against hourly values centered on the satellite image time. The relative RMSE corresponding to the May 1995–January 1996 is 85 W/sq.m, that is 23% in relative terms, and well in line with earlier satellite evaluations for Albany (Perez *et al.*, 1994).

Hence, in terms of RMSE, the satellite breaks even with extrapolation at 34 km (21 miles) as shown in Fig. 5. This is considerably shorter than the previously reported break-even distance for daily irradiance of 50 km, and quite consistent with our expectations (Perez *et al.*, 1994). Indeed, the main source of error for the satellite—determination of cloud thickness and turbidity—is considerably less sensitive to the effect of time scale than the source of error for ground (inter)extrapolation—spatial cloud structures.

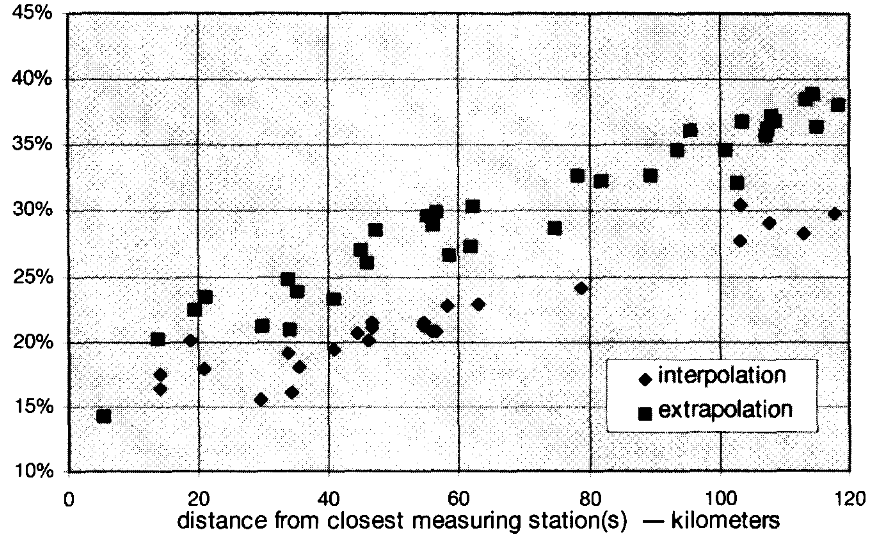

Fig. 4. Interpolation RMSE as a function of the closest site distance.

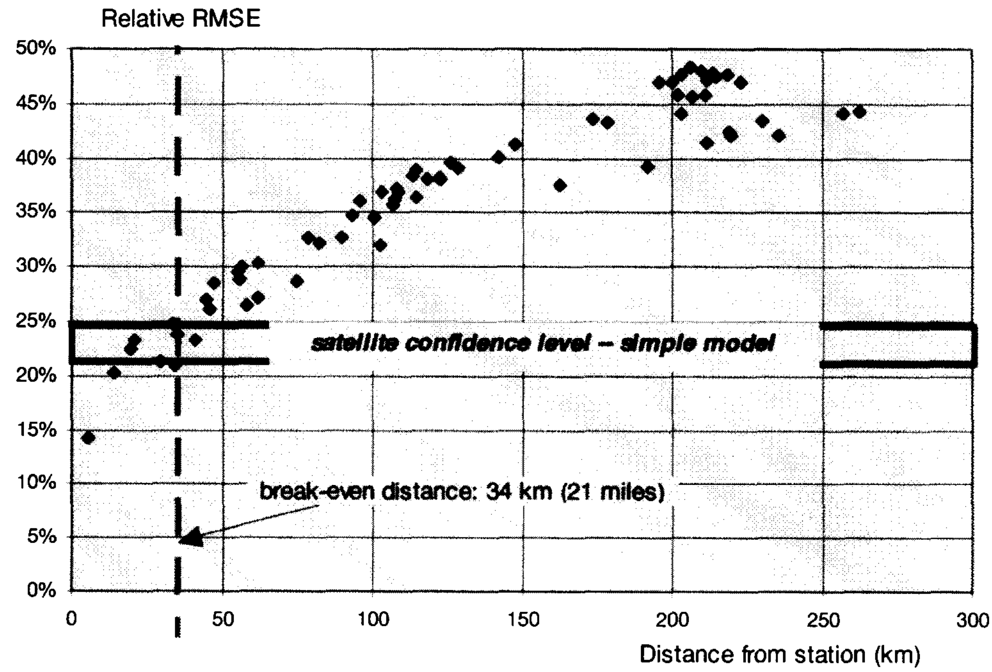

Fig. 5. Satellite prediction accuracy relative to the ground-based extrapolation.

This result is remarkable given the preliminary nature of the considered satellite algorithm that:

- did not account for evolving ground albedo,
- did not operate with a thoroughly validated clear sky model,
- did not account for pixel–sun geometry (i.e. the relevant pixel for a considered station may not always be the closest, but another pixel or a combination of the closest and other pixels, depending on the position of the sun in the sky),
- did not include *a posteriori* ground truth navigation (pixel position) verification.

It is interesting to compare the relationship between satellite-estimated irradiance and ground-measured irradiance (Fig. 6) and the relationship between two stations exhibiting an RMSE of the order of the satellite's (Fig. 7). The noise patterns are similar overall, with a couple of interesting differences. The center core of the extrapolation pattern is tight and the distribution of outliers is gradual and quite symmetrical. The center core of points for the

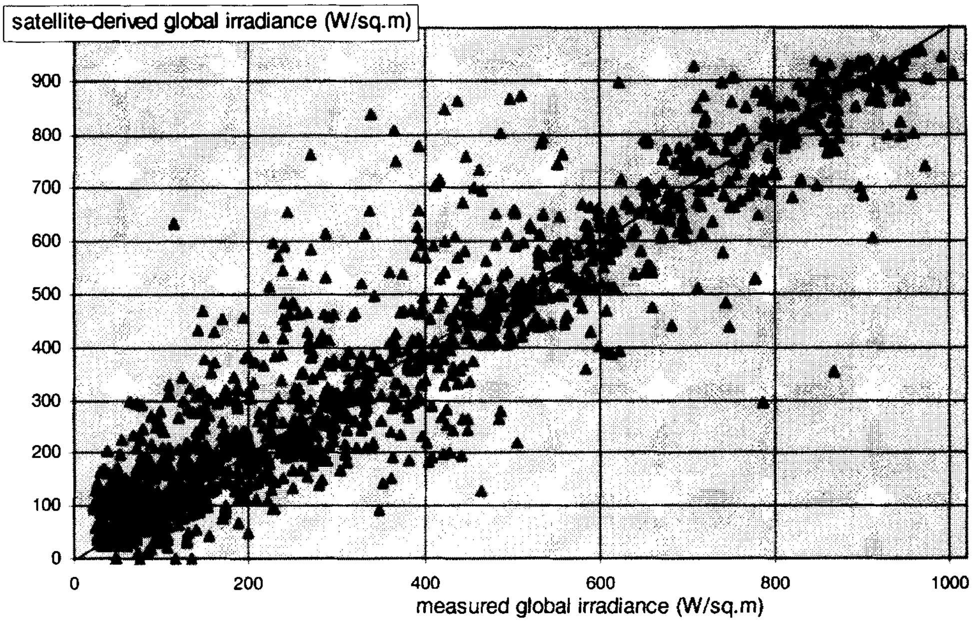

Fig. 6. Satellite derived irradiance vs. hourly ground measurements in Albany.

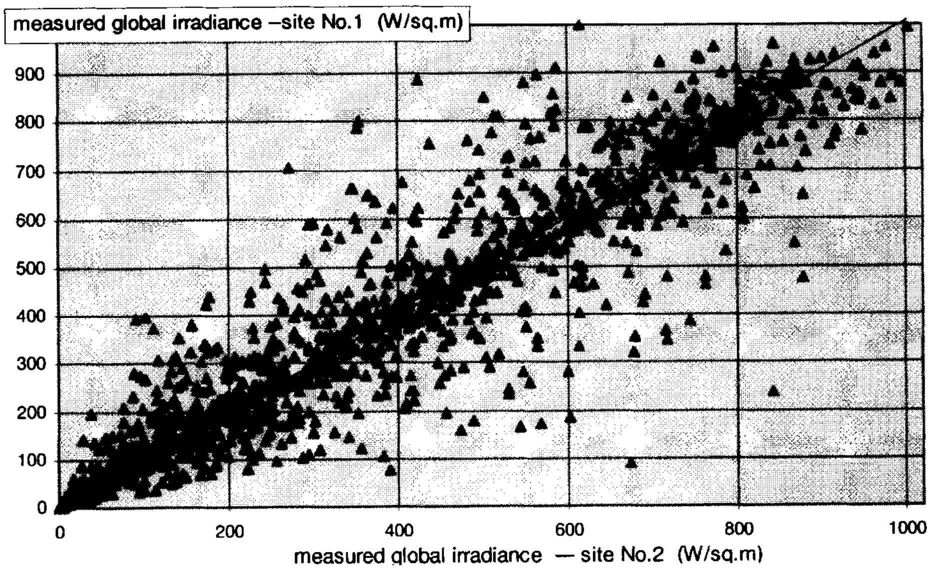

Fig. 7. Comparative hourly global irradiance at two sites 34 km apart.

satellite is not quite as tight—likely a byproduct of the satellite's algorithm limitation in terms of turbidity estimation; outliers are both fewer and more scattered.

Addressing the source of error of these outliers may be a worthwhile avenue to explore to improve satellite models. Concerning this latter point, it is interesting to note that, when comparing satellite estimates against 10 min ground truth values, the RMSE increases slightly to 26%. However when comparing the satellite estimates against any one of 10 min measurements within half an hour of the satellite image time, the lowest achievable RMSE goes down to 17%—that is of the order of the nugget effect mentioned earlier. During variable conditions, the satellite estimate is representative of the ground measurement at least at some point in time within the hour surrounding it.

5. FURTHER RESEARCH

Several avenues of research are being explored as a logical follow-up to this work, including:

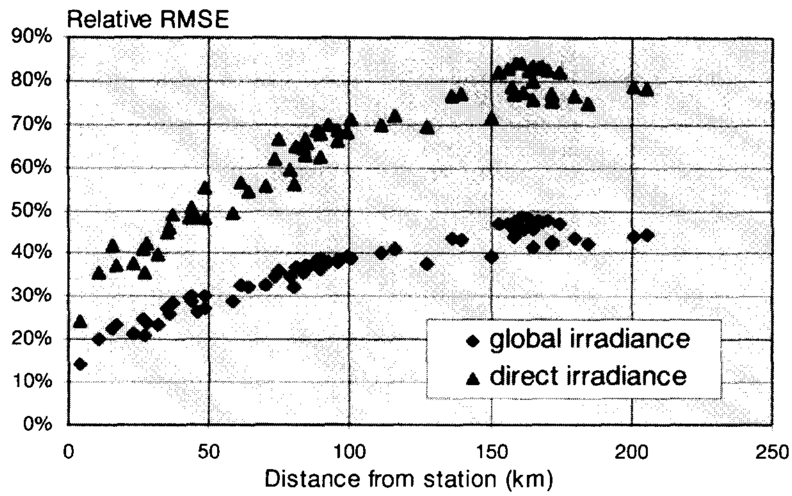

Fig. 8. Relative extrapolation error of direct irradiance compared to global irradiance.

(1) The investigation of other radiation components such as direct irradiance, tilted irradiance, illuminance, etc. As a preliminary finding of this effort, we present, in Fig. 8, the observed extrapolation RMSE of direct irradiance compared to global, showing a considerable error increase for direct.
(2) The evaluation of ground-aided satellite methods, whereby satellite estimates could be corrected using strategically located ground network stations.
(3) The systematic improvement of the pixel-to-irradiance algorithm, including some of the obvious steps mentioned above.
(4) The comparative investigation of other satellite algorithms.

6. CONCLUSION

We compared hourly site/time global irradiances obtained via extrapolation and interpolation of ground stations, to that obtained by processing widely distributed satellite images with a preliminary test model representative of existing statistical models.

Results show that, for hourly data, the satellite becomes more accurate than a local ground station if the distance from the station exceeds 34 km (21 miles), down from a previously reported 50 km range for daily irradiances.

For a regularly spaced network, the break-even distance is estimated to be 50 km (see Fig. 4). Hence, for a country the size of the U.S.A., it would take at least 800 ground stations on a 100 km grid to surpass the site/time specific accuracy already achievable today with geostationary satellites.

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