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Satellite Techniques of Solar Resource Assessment for Focusing and Non-Focusing Solar Collector Systems

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INTRODUCTION

In the previous project periods, techniques were developed for GOES satellite estimates of daily total global horizontal, direct normal, and global tilted-surface insolation (Justus, 1985). Daily and monthly mean insolation values estimated from the satellite data were compared with those observed at the Georgia Tech insolation monitoring site. These results indicated the basic accuracy (based on rms deviation from observed) to be about 4.9% for monthly mean global horizontal insolation or 6.7% or the monthly mean direct normal (see Figures 1 and 2).

With the ultimate goal of developing an atlas of the solar energy resources for the country of Saudi Arabia, by the use of satellite estimation techniques, the previous and current (final) year's activity involved study of techniques for the use of METEOSAT data to estimate global horizontal and direct normal insolation. Since one or more years of METEOSAT data would be very expensive to acquire, the scope of the project was to examine a small number of days of insolation from the Riyadh monitoring site with the corresponding METEOSAT data. The primary purpose was to determine if the bright sandy surface (which limits the contrasting signal between clear and cloud conditions) or the large satellite zenith angle for Saudi Arabian sites would cause any problems. A second purpose was to determine if the METEOSAT data could be used to determine the expected large variations in clear-sky direct and global insolation due to optically thick aerosol and dust clouds which are frequently present.

Study of both summer and winter clear days (Justus, 1986) indicated that the brightness of the sandy surface and the satellite viewing angle will present no problems. Results from clear days indicated, however, that because of large variations due to optically thick aerosol and dust layers the METEOSAT visible sensor data alone was not able to provide accurate hourly direct normal insolation estimates. The major focus of this study is to determine whether information from the thermal IR channel of METEOSAT can be used to improve the satellite estimates of direct normal insolation on cloud-free days, and to develop and test algorithms for estimating both direct normal and global horizontal insolation under both cloudy and cloud-free conditions.

DEVELOPMENT OF THE INSOLATION ALGORITHMS

The general form of the model equations used to calculate hourly total direct normal and global horizontal insolation is given by (Justus, 1985)

$$\mathrm{Dir} = \mathrm{Dir(Clr)} - \Delta\mathrm{Dir}, \quad (1)$$

and

$$\mathrm{Glo} = \mathrm{Glo(Clr)} - \Delta\mathrm{Glo}. \quad (2)$$

Dir(Clr) and Glo(Clr) are model-calculated values of direct normal and global horizontal surface broad-band irradiance under cloud-free conditions (Justus and Paris, 1985). The terms ΔDir and ΔGlo are the departures from cloud-free irradiance which are due to cloud cover. These may be computed either by a model for broad-band irradiance through clouds (see Figures 21 and 22 of Justus, 1985 or Figure 1 of Justus, 1986), or by empirical relations derived from comparison between measured surface irradiance and satellite-measured brightness (count) values (see equations 4 and 6 of Justus, 1985).

Hourly values of direct normal and global horizontal irradiance measured at the Riyadh site have been compared with simultaneously observed shortwave radiances measured by the visible channel of the METEOSAT satellite. These data are shown in Figures 3 and 4 in the form of the reduction in irradiance below that calculated from nominal atmospheric conditions with the clear-sky model plotted versus the increase in satellite-measured radiance counts from those expected under the same clear-sky atmospheric conditions. Nominal atmospheric conditions assumed are an aerosol optical depth of 0.3 (at 500 nm). The desert surface albedo is assumed to be 0.45 within the spectral range of the METEOSAT visible sensor, and the METEOSAT calibration of Koepke (1982) is assumed for purposes of calculating the expected clear-sky sensor counts.

The solid line in Figure 3 provides an estimate of insolation from satellite-observed counts via

$$\text{Glo} = \text{Glo(Clr)} - 13.85(\text{Counts} - \text{Clear Counts}) \quad , \qquad (3)$$

while the solid line in Figure 4 can be expressed as

$$\text{Dir} = \text{Dir(Clr)} \, [\, 1. - 0.02835(\text{Counts} - \text{Clear Counts})] \quad . \qquad (4)$$

For some cases, these relations will provide adequate estimates of direct normal and global horizontal irradiance. However, both Figures 3 and 4 show a substantial number of data points, measured under apparently cloud-free conditions, for which slight reductions in surface insolation are accompanied by substantial reductions in satellite-measured visible radiance counts below that expected for clear-sky conditions (negative values of Counts - Clear Counts). These cases are due to overcast aerosol or dust layers which reduce the insolation (with the direct normal affected more than the global horizontal), while not increasing (or perhaps even decreasing) the amount of reflected radiation seen by the satellite. In Figure 4, there are also a substantial number of cases in which there is a considerable reduction in surface direct normal irradiance (values of relative direct irradiance from about 0.5 to 1) without a corresponding increase in the satellite-measured visible radiance counts. Some of these may be due to thin, patchy clouds which substantially reduce the direct normal hourly average (without much effect on the global irradiance), but are not reflective enough to significantly increase the reflected radiation seen by the satellite.

For these problem areas, the ability of satellite-measured infrared radiance counts (IR) to improve the insolation estimates over that found by using the satellite-measured visible radiance counts (VIS) only has been examined by evaluating a multiple regression relation between surface irradiance and both of these satellite measurements. The results are expressed as

$$\text{Glo} = \text{Glo(Clr)} + 0.1685[\text{VIS} - \text{VIS(Clr)}] - 3.918[\text{IR} - \text{IR(Clr)}] \quad , \qquad (5)$$

and

$$Dir = Dir(Clr)\{1 - 0.01338[VIS - VIS(Clr)] - 0.01948[IR - IR(Clr)]\} . \quad (6)$$

The ability of the VIS-only relations (equations 3 and 4) or the VIS+IR relations (equations 5 and 6) to reproduce the observed surface direct normal and global horizontal irradiance are examined in the following section.

EVALUATION AND TESTING OF THE INSOLATION ALGORITHMS

For cloud-free days without substantial overcast aerosol or dust layers, such as shown in Figures 5 and 6 for Day 348, 1982, and for cases with substantial cloud influence, such as shown in Figures 7-10 for Days 53, 1982 and 105, 1984, the VIS-only technique adequately reproduces the observed direct normal and global horizontal irradiance. For some specific hours problems arise, such as with the direct normal values at hour 17 on the two cloudy days, and with both the direct normal and global horizontal irradiance at hour 11 on day 105, when a small observed satellite-measured visible radiance counts would indicate substantially larger surface irradiance values than are observed at the Riyadh site.

Some of these problems are due to the inherent mismatch between satellite-measured values and the corresponding surface irradiance data. The surface irradiance is averaged over an hourly period at one location (the Riyadh site), while the satellite-measured radiance is essentially a "snapshot" value of reflected radiation made near the beginning of the hour. The mismatch can be partially (but not completely) compensated by using satellite radiance averaged over an approximately 40 × 40 km target area as a surrogate for the hourly averaging process at the individual surface site. The type of errors caused by this mismatch problem tend to be somewhat random and tend to partially cancel when daily and monthly averaged data are considered (e.g. hourly rms errors of the order of 15%, daily rms errors of the order of 10%, and monthly rms error of the order of 5%).

For cloud-free days with substantial overcast of aerosol or dust layers, as illustrated by day 167 for 1982, 1983 and 1984, shown in Figures 11-16, the VIS-only technique of equations 3 and 4 significantly overestimates the observed global horizontal and direct normal irradiance, while the VIS+IR technique of equations 5 and 6 offers substantial improvement in the irradiance estimates.

CONCLUSIONS

For cloudy days or days with partial cloud cover, and for cloud-free days without substantial overcast of aerosol or dust layers, the VIS-only technique of equations 3 and 4 provides adequate accuracy for estimating global horizontal and direct normal insolation from the satellite-measured visible radiance counts. For days with substantial overcast of aerosol or dust layers, the VIS+IR technique of equations 5 and 6 provides the additional information necessary for estimating surface direct normal and global horizontal irradiance.

Combined with the results from the earlier studies, that the bright desert background and the large satellite viewing angles present no substantial problems, these results mean that monthly average direct normal and global horizontal irradiance estimates of comparable accuracy to those estimated for the Georgia Tech site from GOES data (Figures 1 and 2), should be achievable from METEOSAT observations over Saudi Arabia.

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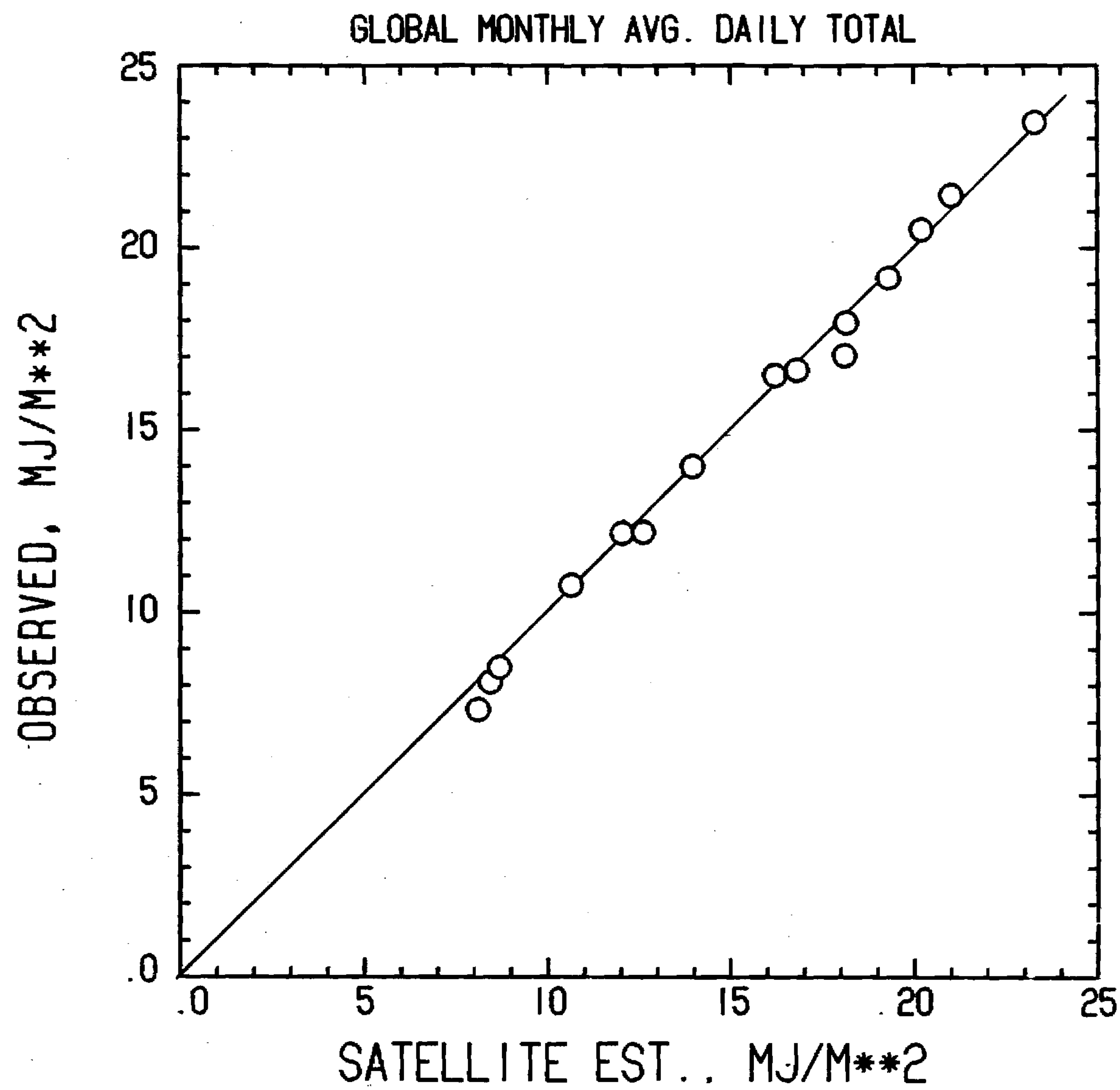

Figure 1 - Monthly averaged daily total global horizontal irradiance observed at Georgia Tech versus that estimated from the GOES satellite.

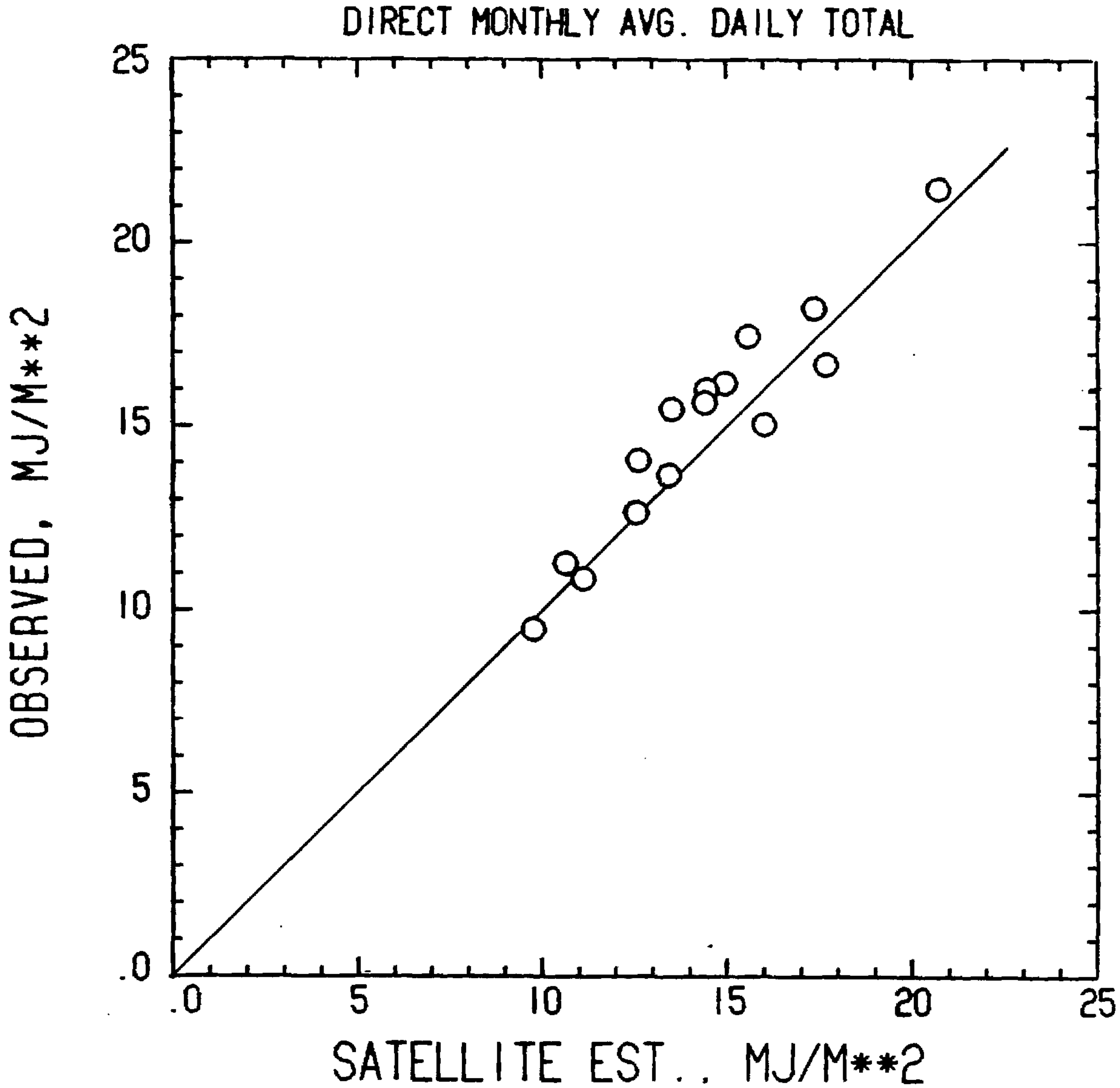

Figure 2 - Monthly averaged daily total direct normal irradiance observed at Georgia Tech versus that estimated from the GOES satellite.

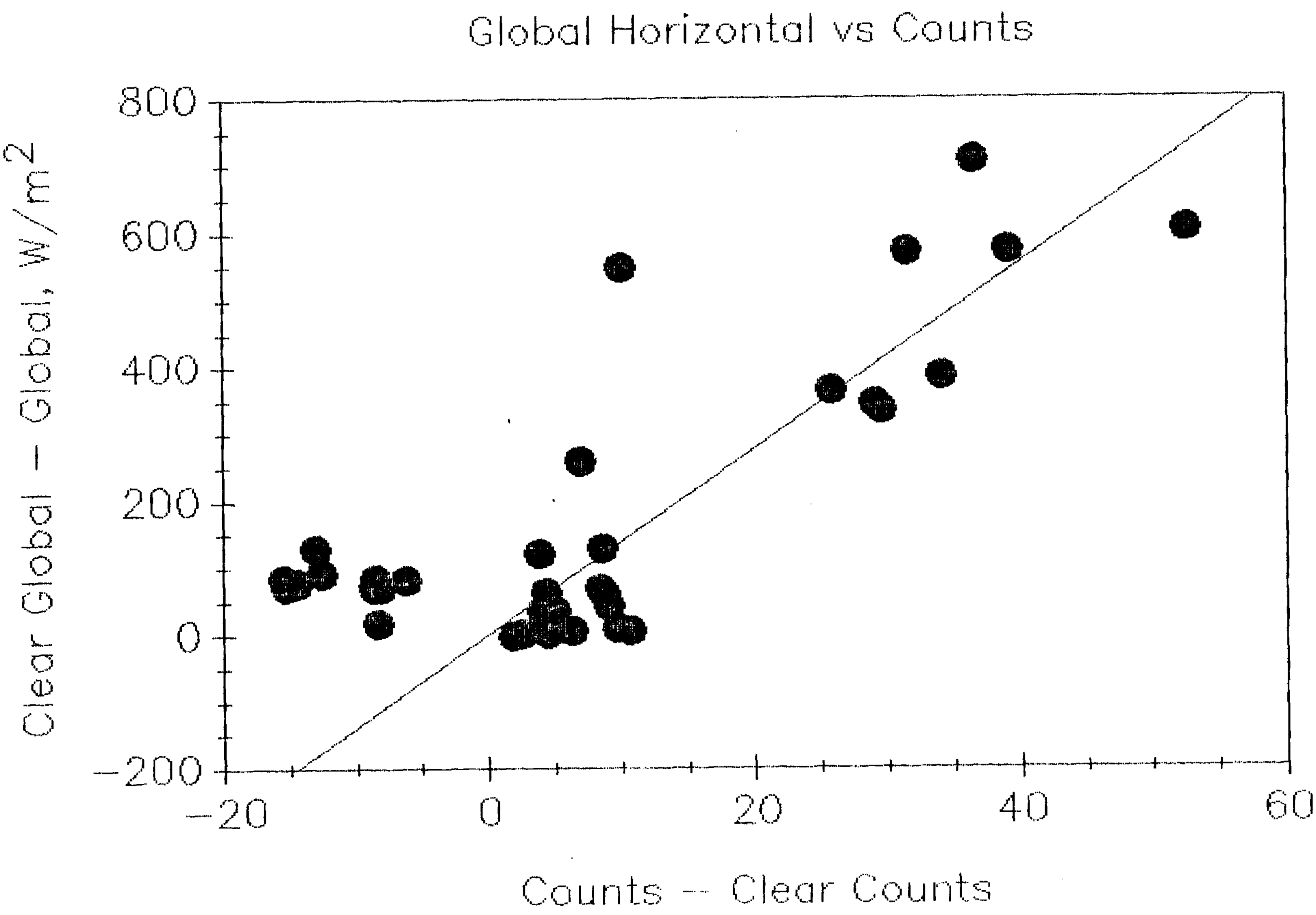

Figure 3 - Observed hourly global horizontal irradiance, relative to clear global, versus the observed METEOSAT radiance counts, relative to the counts expected under cloud-free conditions.

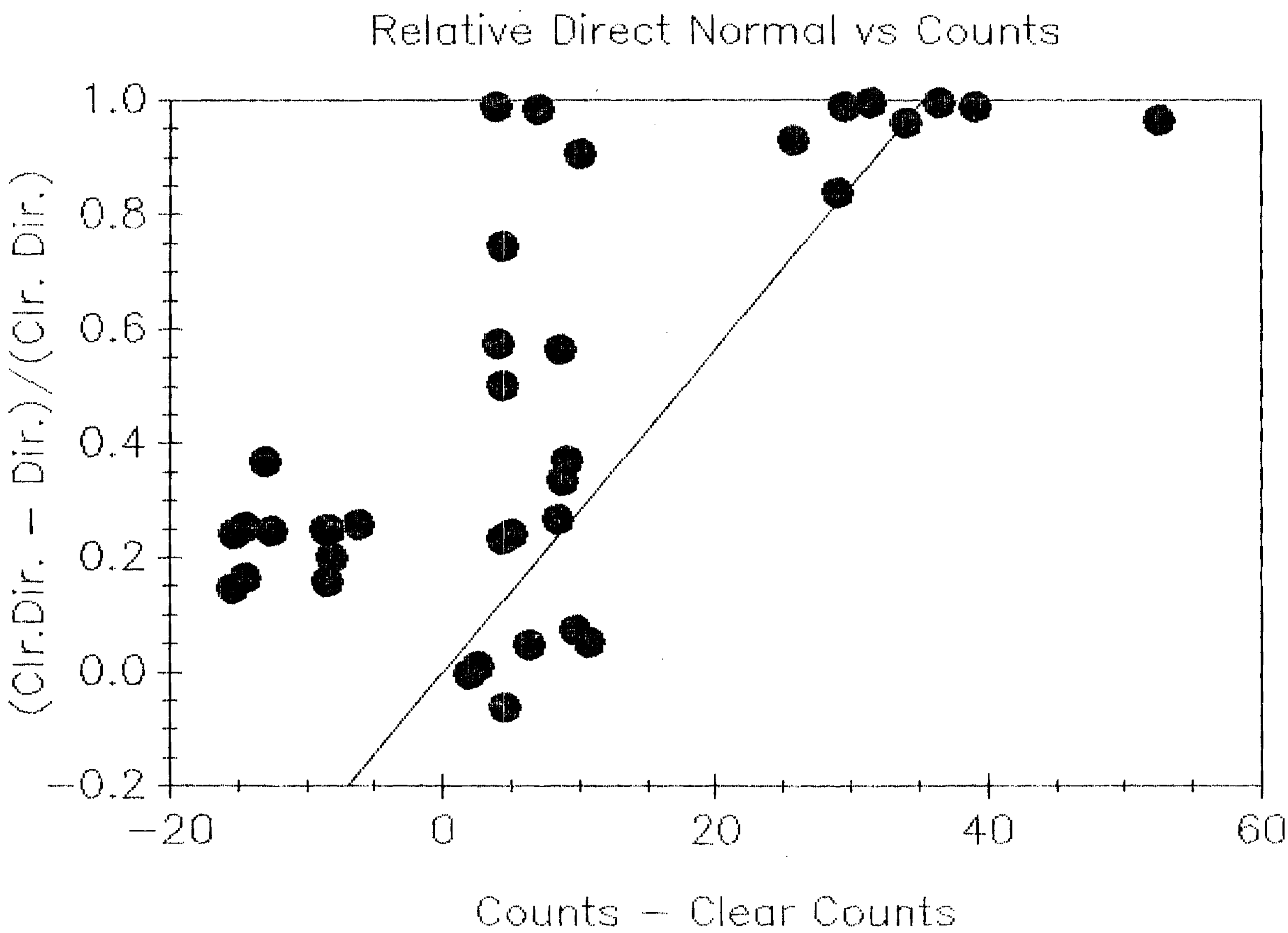

Figure 4 - Observed hourly direct normal irradiance, relative to clear direct, versus the observed METEOSAT radiance counts, relative to the counts expected under cloud-free conditions.

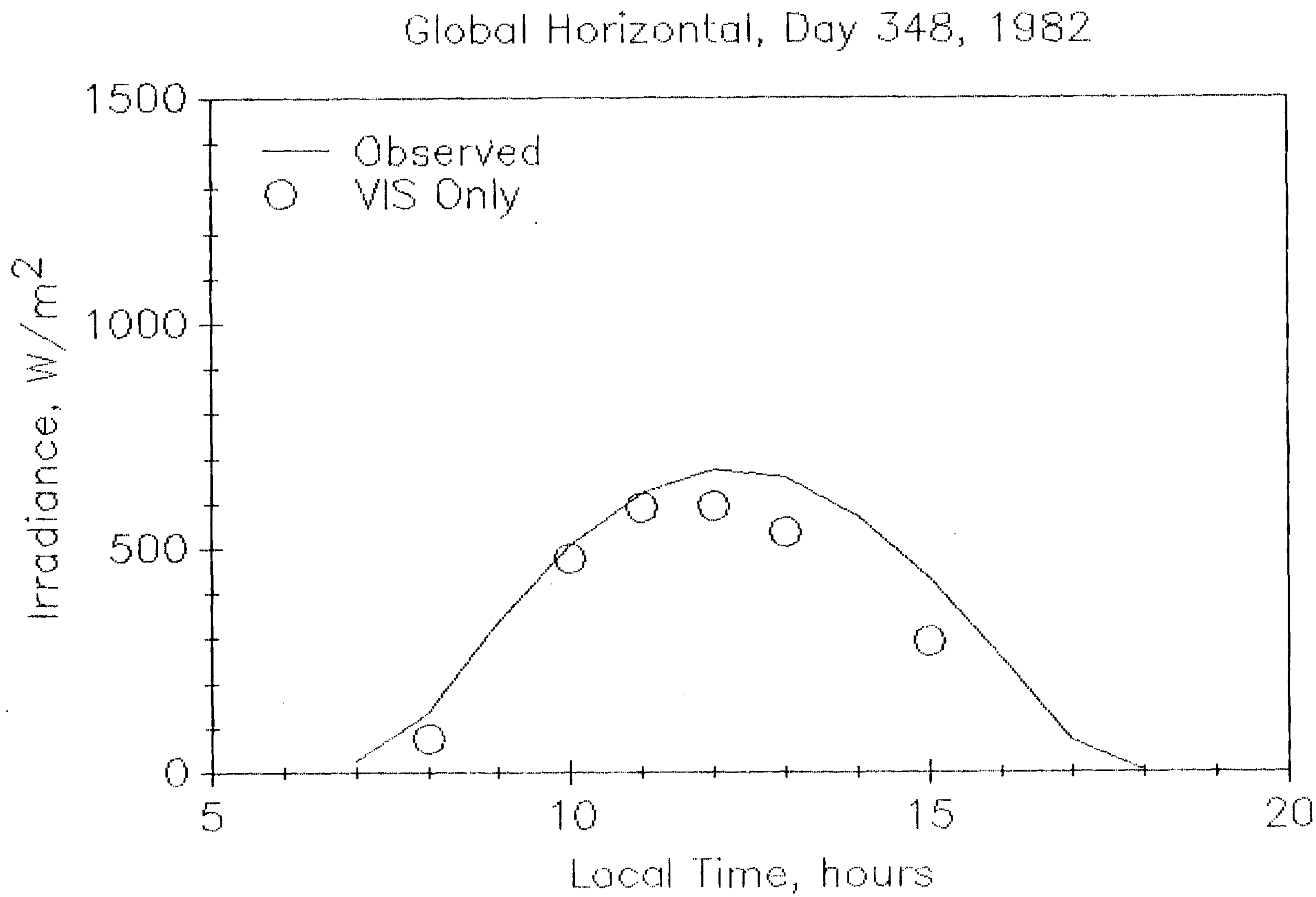

Figure 5 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 348, 1982, using the VIS-only technique.

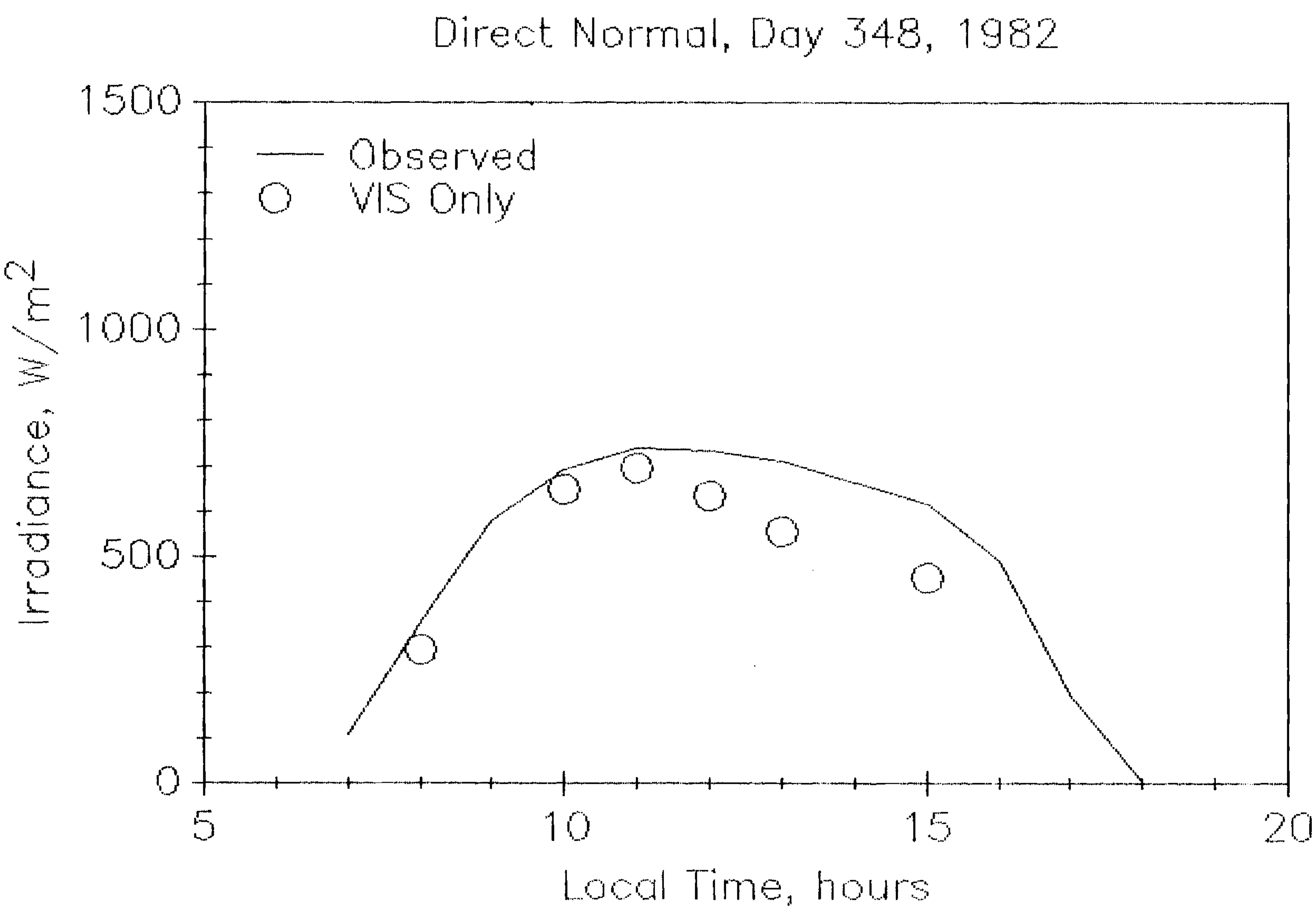

Figure 6 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 348, 1982, using the VIS-only technique.

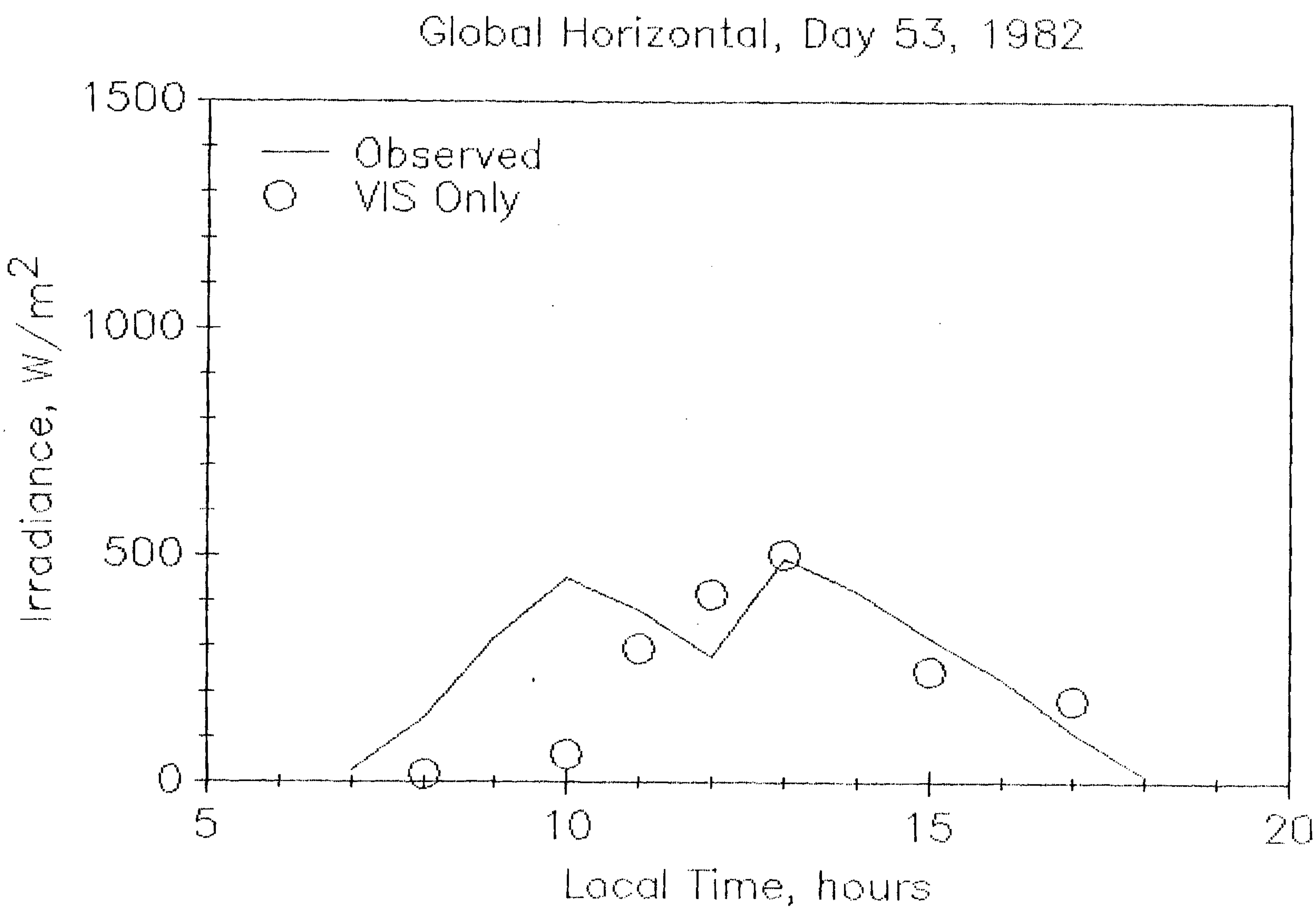

Figure 7 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 53, 1982, using the VIS-only technique.

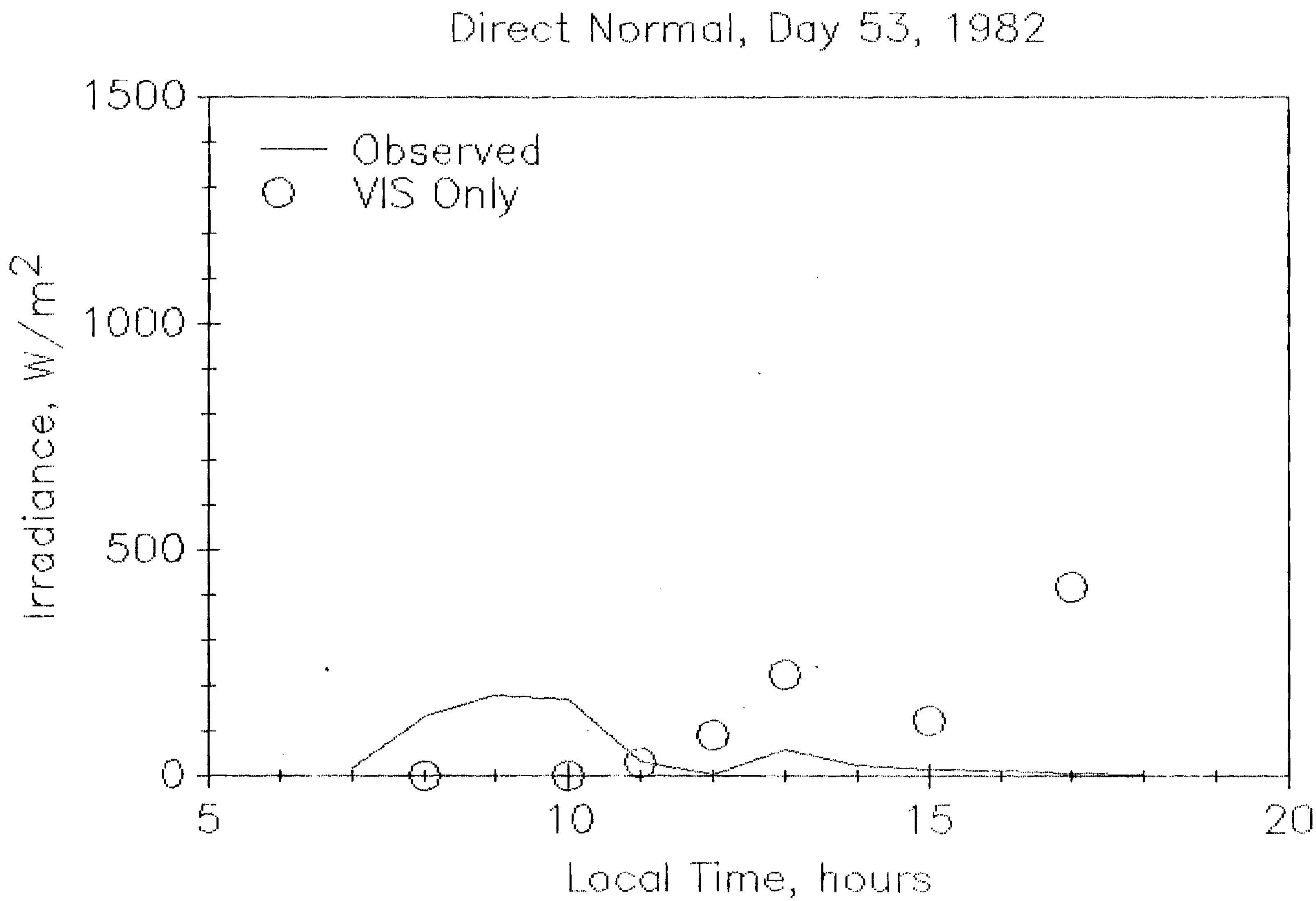

Figure 8 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 53, 1982, using the VIS-only technique.

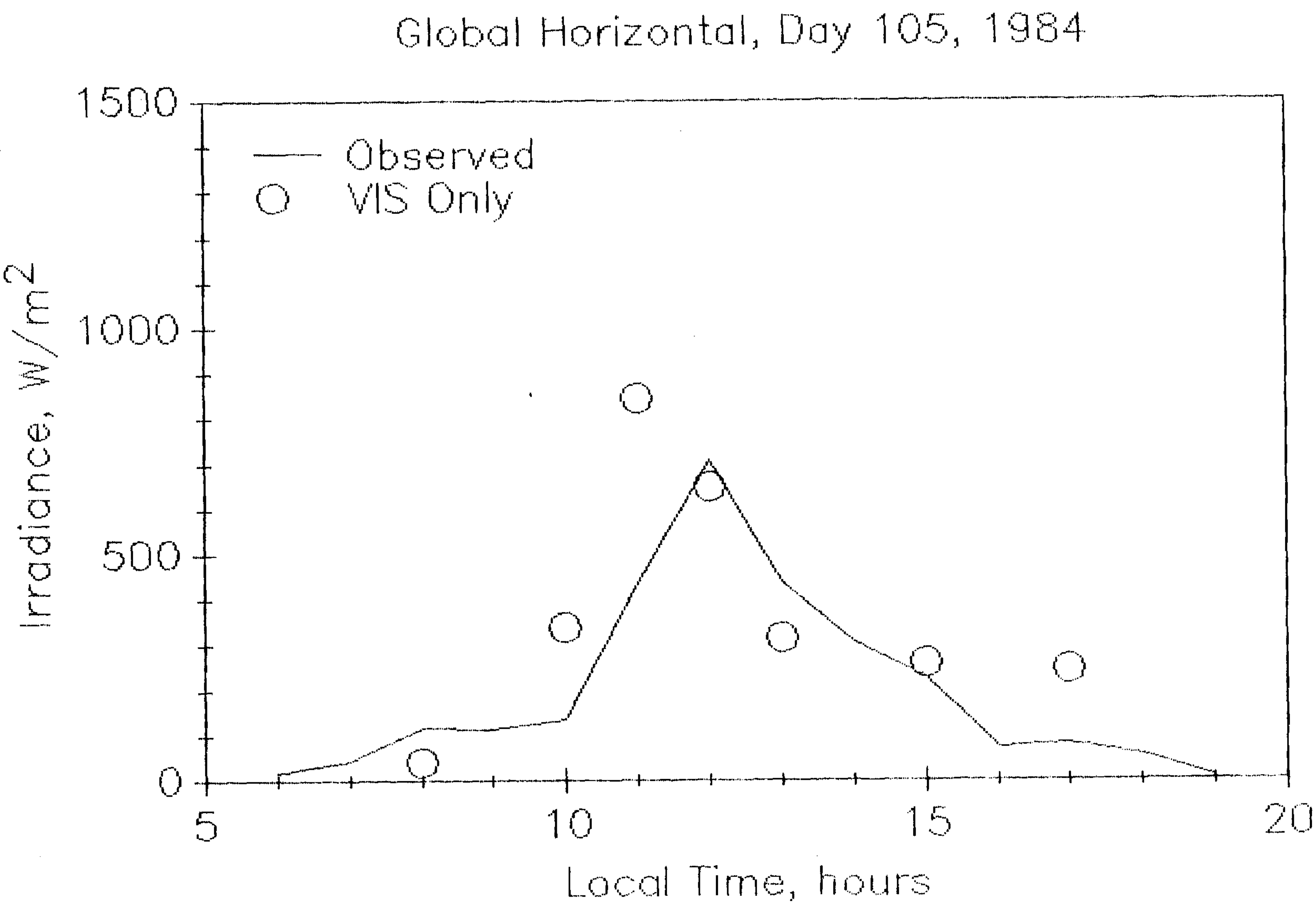

Figure 9 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 105, 1984, using the VIS-only technique.

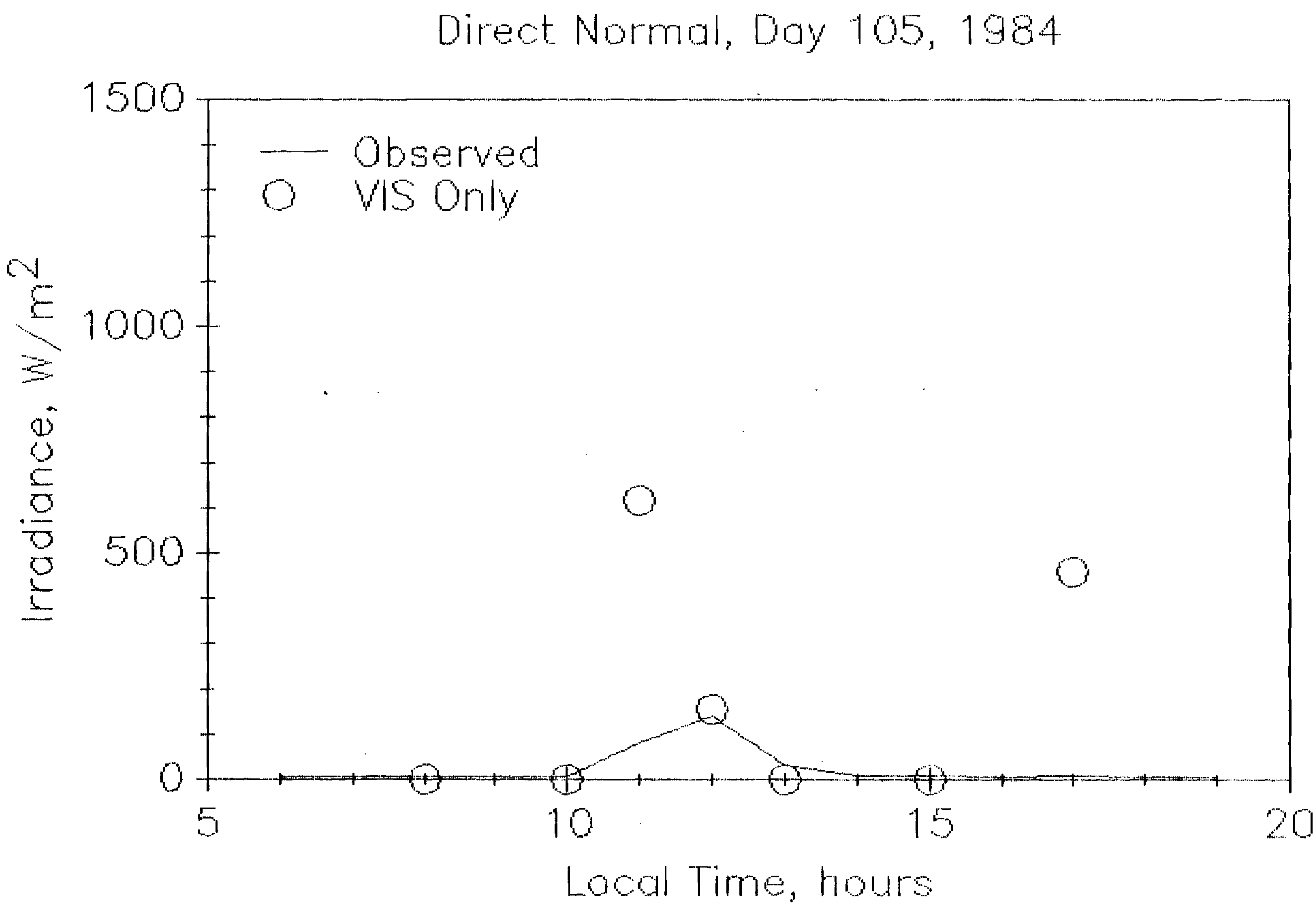

Figure 10 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 105, 1984, using the VIS-only technique.

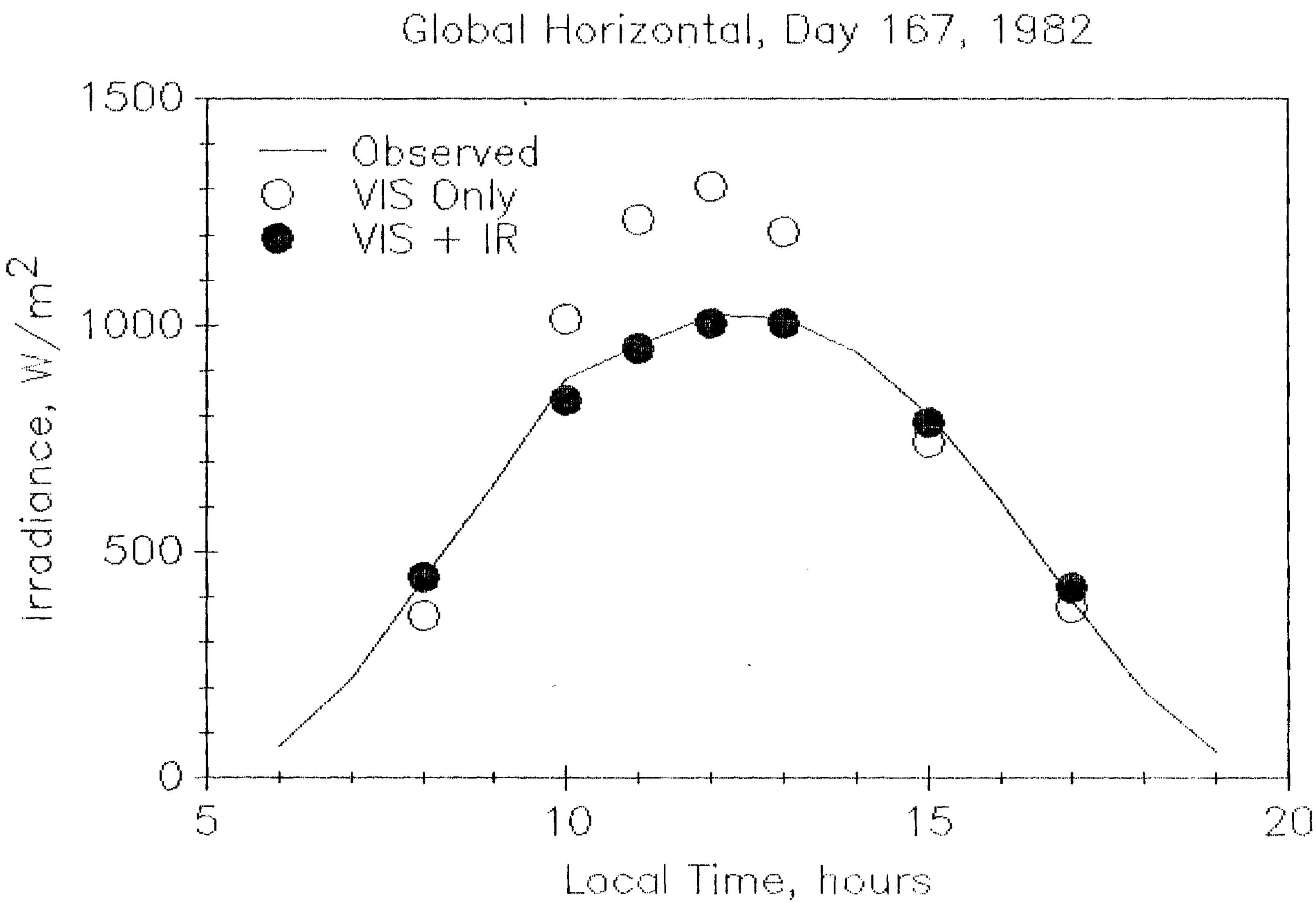

Figure 11 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 167, 1982, using the VIS-only and the VIS+IR techniques.

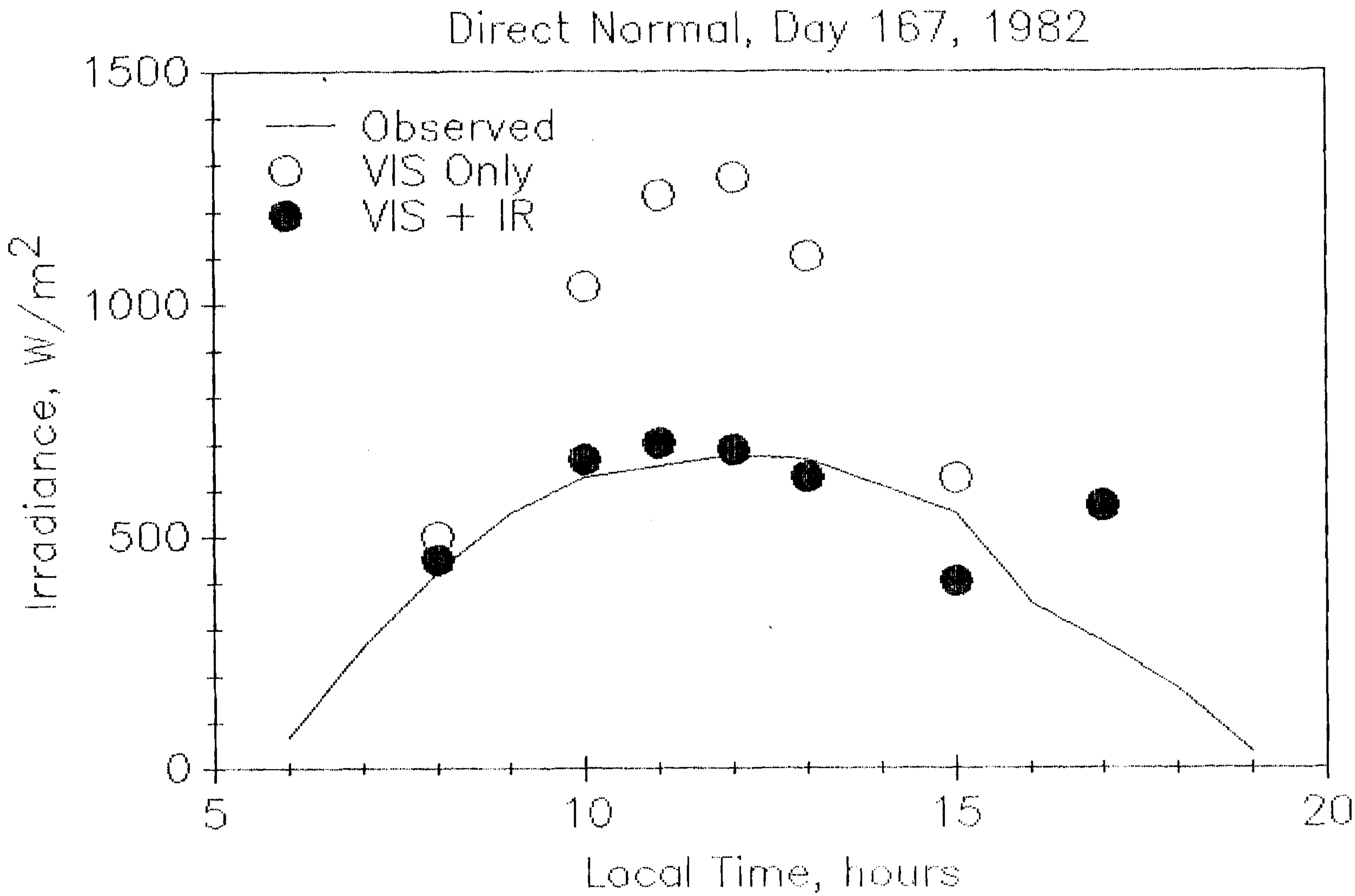

Figure 12 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 167, 1982, using the VIS-only and the VIS+IR techniques.

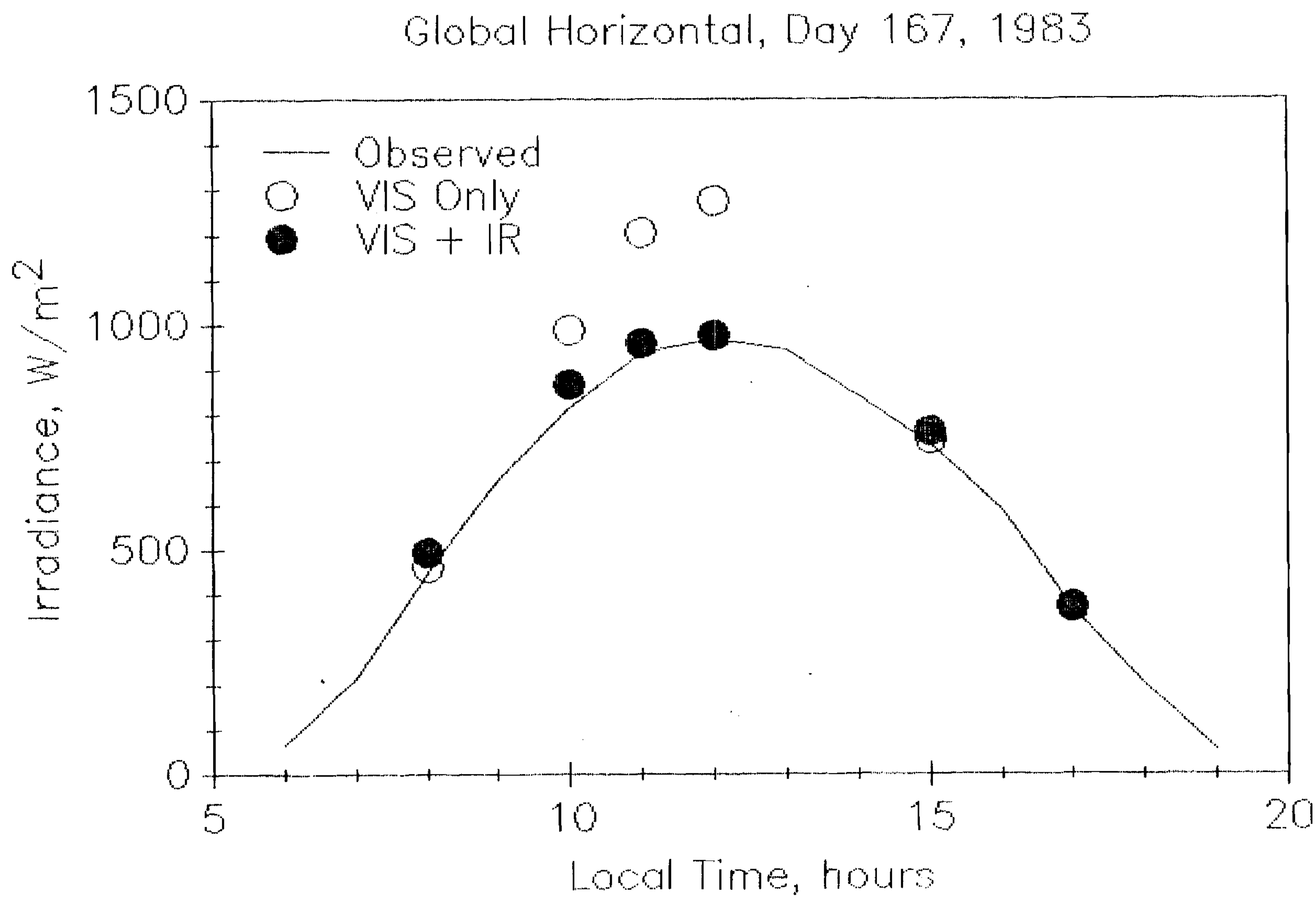

Figure 13 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 167, 1983, using the VIS-only and the VIS+IR techniques.

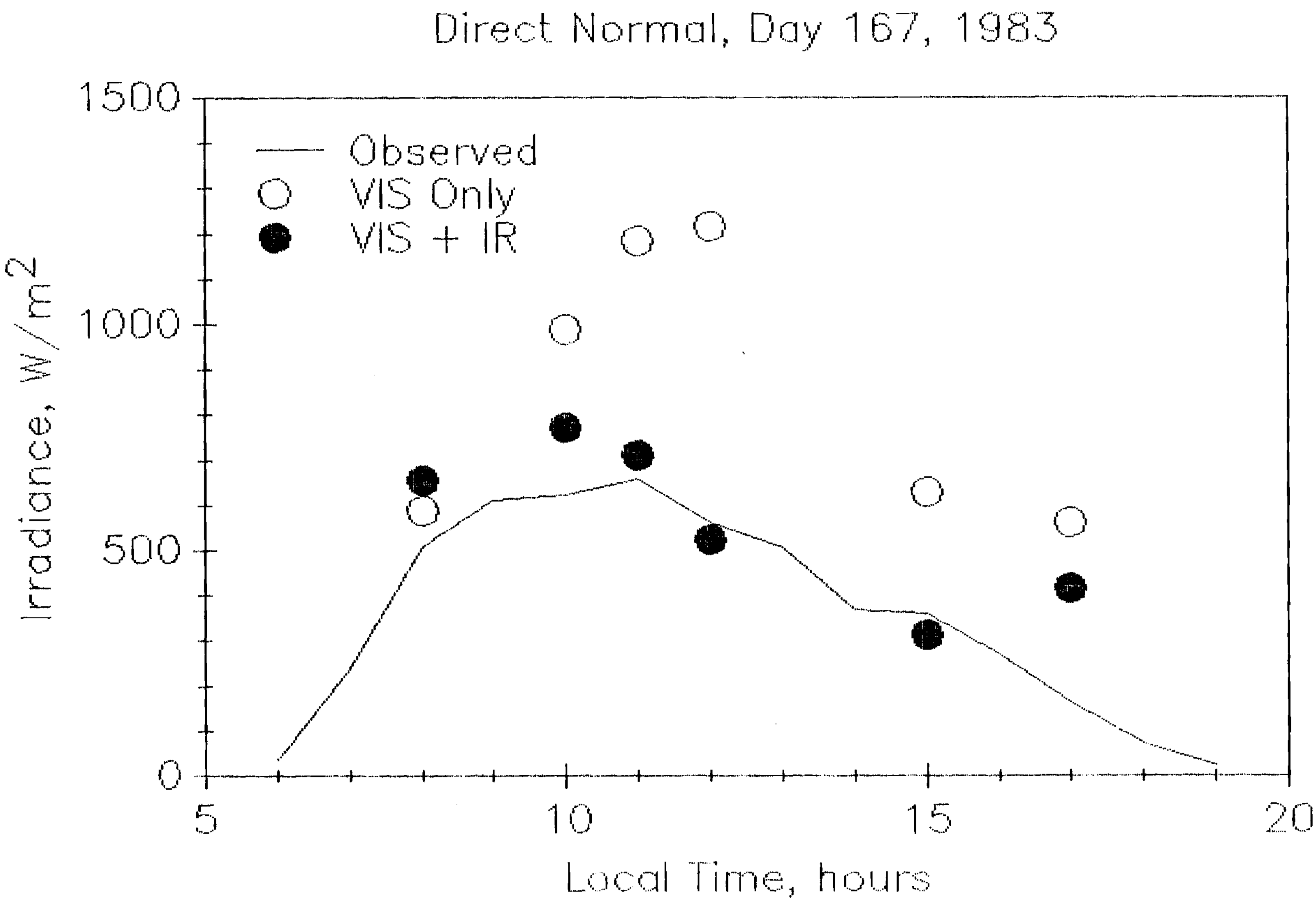

Figure 14 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 167, 1983, using the VIS-only and the VIS+IR techniques.

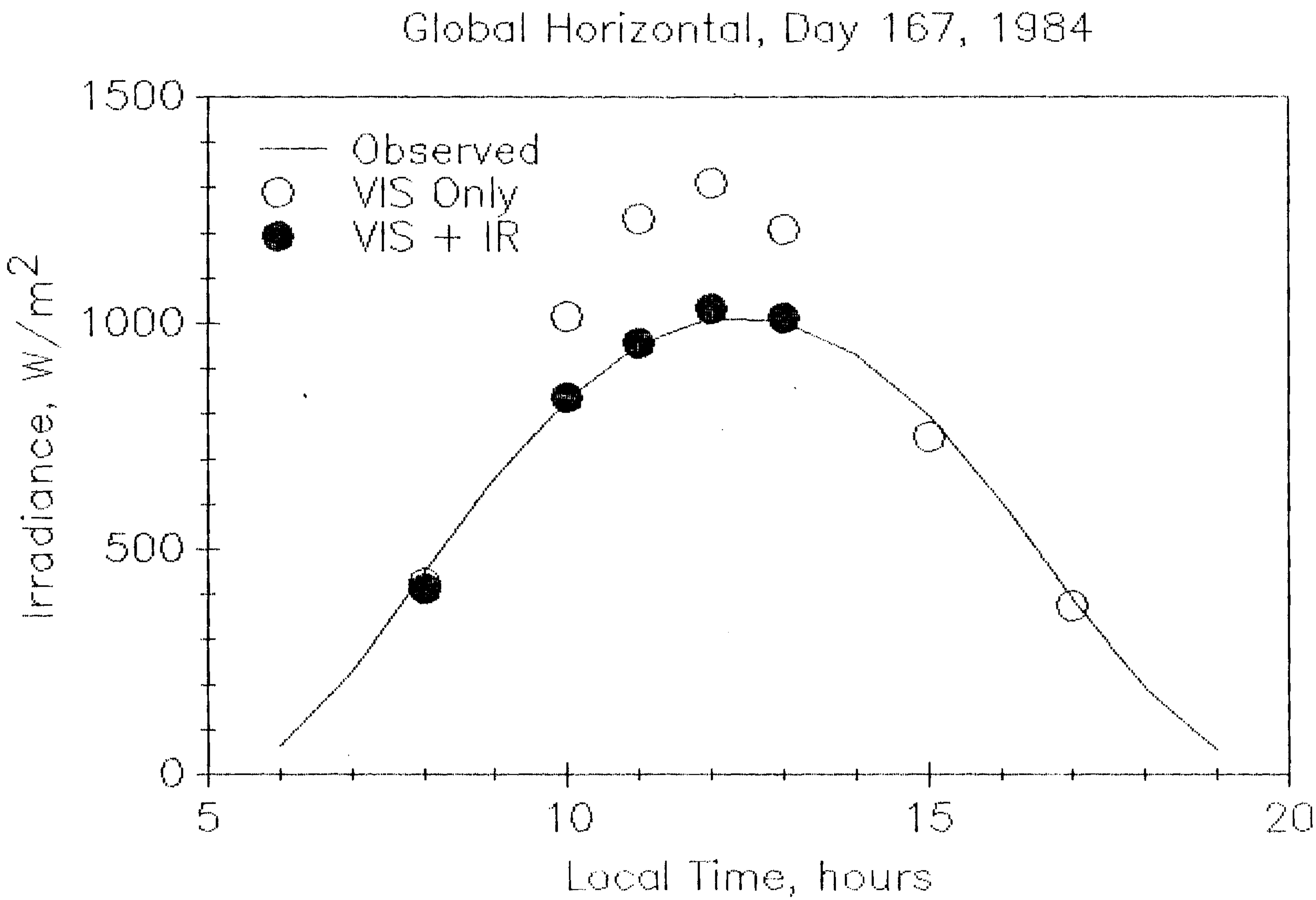

Figure 15 - Time series plot of hourly satellite-estimated global horizontal irradiance compared with observed values, for Day 167, 1984, using the VIS-only and the VIS+IR techniques.

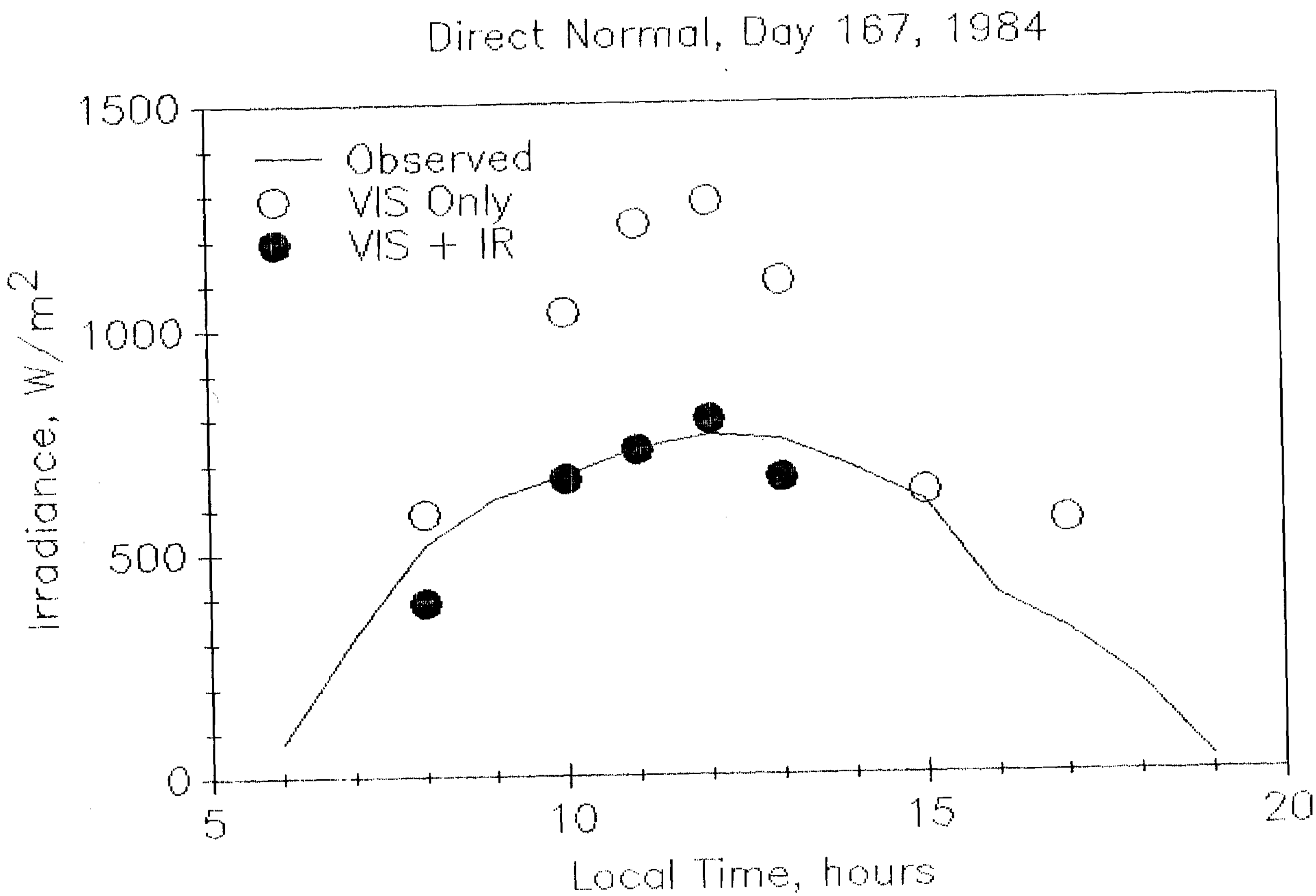

Figure 16 - Time series plot of hourly satellite-estimated direct normal irradiance compared with observed values, for Day 167, 1984, using the VIS-only and the VIS+IR techniques.