A Single-Channel, Double-Viewing Angle Method for Sea Surface Temperature Determination from Coincident METEOSAT and TIROS-N Radiometric Measurements

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ABSTRACT

An experimental simulation of a single-channel, double-angle viewing technique for the determination of sea surface temperature from satellite is presented. This method relies upon the fact that the same area can be viewed simultaneously at two different angles (different air masses) by the geostationary satellite METEOSAT and by the polar orbiting satellite TIROS-N. Extrapolating the two air mass observations to zero air mass is shown to give a value of the temperature in good agreement with the true sea surface temperature. A discussion concerning the viewing angles is presented.

1. Introduction

The importance of global monitoring of sea surface temperature (SST) for an increased knowledge of various processes related to the interaction between oceans, air–sea and climate systems has long been recognized. As it is well known, the problem found in remotely determining the SST deals with the atmospheric emission and absorption. In most of the approaches published in the recent past, the atmospheric correction is determined through a regression fit using measurements in two or more spectral channels. The differential aspect of such methods proceeds from wavelength variations. Although a number of studies have been undertaken in order to improve our knowledge of the spectroscopic aspect of the absorption (lines and continua) uncertainties still remain which may result, as shown in Imbault *et al.* (1981), in problems to optimize the spectral domains covered by the sounding channels. It appears that the most efficient differential technique is the multiple (in fact, double) viewing angle technique which allows for the elimination of the uncertainties due to wavelength dependences of the phenomena encountered when using multichannel single-viewing-angle techniques. The use of different angles has been suggested by several authors and, in particular, by Saunders (1967) and McMillin (1975) [see also De Felice and Pontier (1977)]. However, up to now, none of the past or present operational orbiting satellites have offered the possibility of observing the same scene at different viewing angles within a short period of time. However, such a capability may be simulated by coupling simultaneous observations made by a geostationary satellite and by an orbiting satellite, provided the sounding channels aboard each satellite are similar. We present in this paper the results of a study undertaken by coupling the geostationary satellite METEOSAT and the polar orbiting satellite TIROS-N.

2. The double viewing angle technique applied to the coupling of METEOSAT and TIROS-N window channels.

a. *Conversion of METEOSAT observations into equivalent TIROS-N observations*

Since the observations made by TIROS-N and METEOSAT slightly differ, first in the area covered and, second, in the spectral channels (the two filter response functions as well as the two associated weighting functions are not strictly coincident: see Fig. 1), a transformation is applied to the METEOSAT observations in order to adapt them to the TIROS-N observations. This transformation consists in averaging the METEOSAT observed digital count numbers over the TIROS-N spot and in converting the mean number to a radiant energy value through the calibration curve. This value is then converted into an equivalent HIRS/2 channel 8 radiant energy. These three steps have been extensively described in Beriot *et al.* (1982). Let us briefly recall that the conversion algorithm which allows the radiance measured by the METEOSAT radiometer, for a given scene, to be deduced from the radiance effectively measured by a corresponding HIRS/2 channel for the same scene and same zenith angle is obtained using a line-by-line radiance computation model (Scott and Chedin, 1981): synthetic computations of the METEOSAT window channel and HIRS/2 Channel 8 have been carried out for a set of 48 clear-sky atmospheric situations, the surface temperature

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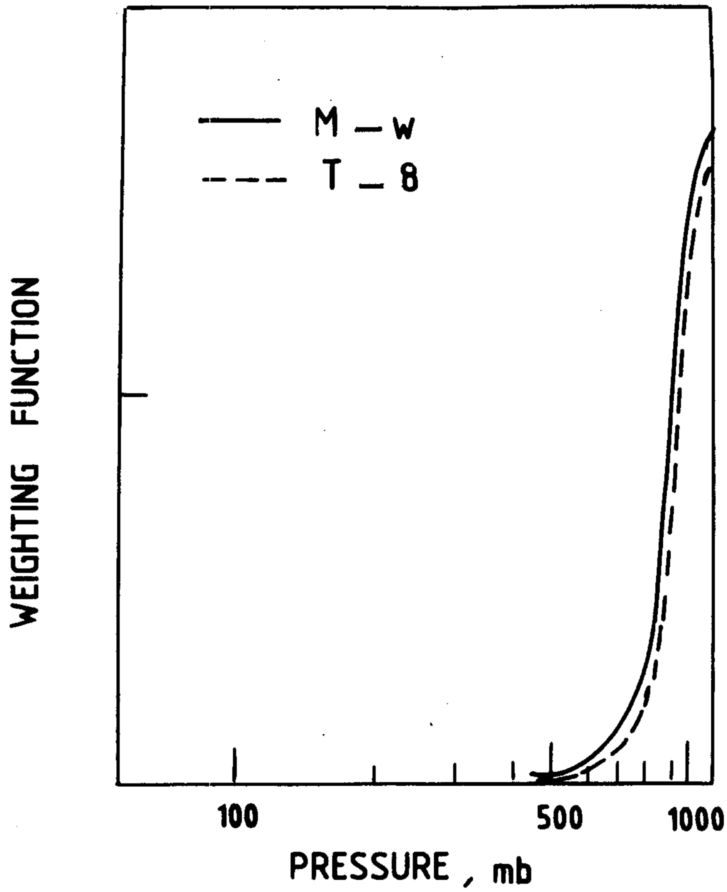

FIG. 1. Weighting function of the METEOSAT window channel (solid line) and weighting function of the TIROS-N HIRS/2 Channel 8 (dashed line) for the same scene (Point "M", 07/09/79).

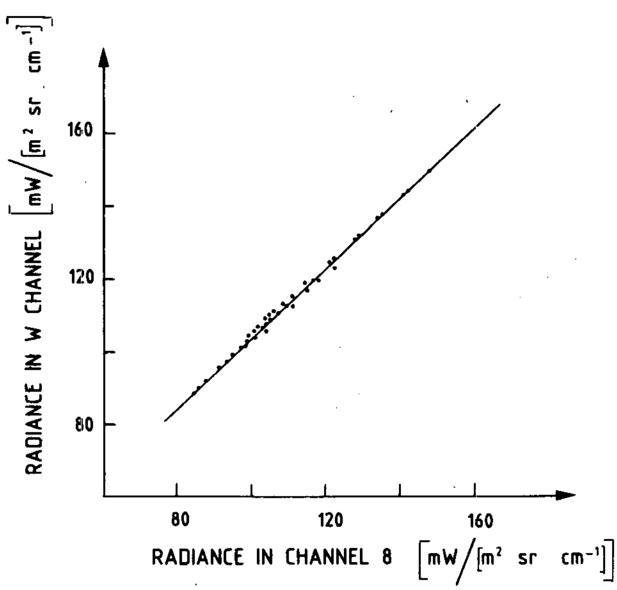

FIG. 2. Computed radiances for the TIROS-N HIRS/2 Channel 8 (x-axis) versus the METEOSAT window channel (y-axis). 48 atmospheric situations are represented. Solid line is the best least-squares fit.

varying from 6 to 56°C and the secant ranging from 1 to 2. Results are presented in Fig. 2.

b. *Sea surface temperature determination*

We collected a set of 23 couples of simultaneous measurements by METEOSAT in the infrared window channel and by TIROS-N in Channel 8 of HIRS/2 (High Resolution Infrared Sounder), both centered around 11 μm. Each couple corresponds to observations of the same scene at two significantly different angles θ_1 and θ_2. The radiant energy value directly measured by HIRS/2 and the value obtained from METEOSAT after the above transformations are plotted against the values of the secant of their respective viewing angles θ_1 and θ_2. The ordinate at the origin of the straight line joining these two points is the radiance value corresponding to an observation with a zero air mass (no atmosphere) which is the radiance emitted by the surface: the sea-surface temperature is easily obtained through the inversion of the Planck function. This procedure is illustrated on Fig. 3 for 12 couples of points among the 23 collected.

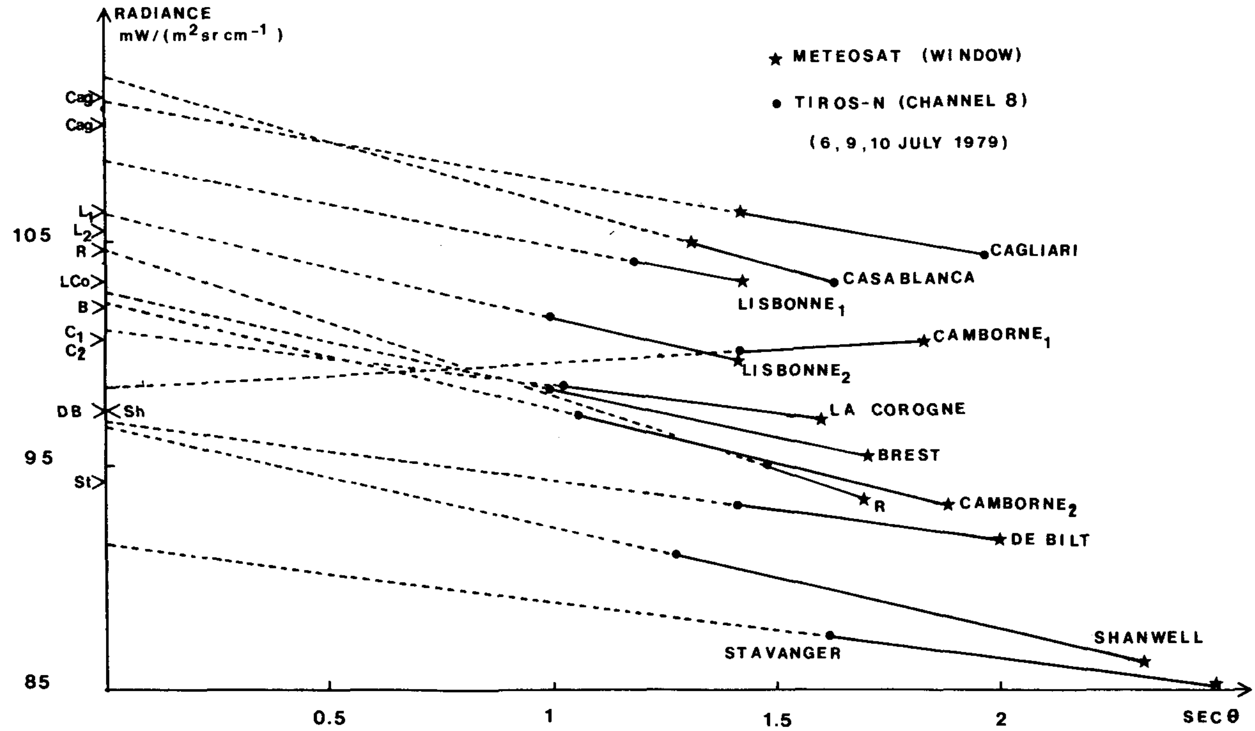

FIG. 3. Radiances observed in Channel 8 of HIRS/2 (dots) and window channel of METEOSAT, transformed to an equivalent HIRS/2 Channel 8 observation (stars), plotted against secθ. Extrapolation to secθ = 0 gives the surface emitted radiance. Observed values are identified along the y-axis by the initial of the station.

Table 1 gives the results of this procedure when applied to the 23 couples of observations. The observed sea-surface temperatures have been obtained from three different sources: the European Meteorological Bulletin, the GOSSTCOMP informations, and ship measurements analysis produced by the French Meteorological Office. Results presented in Table 1 correspond to points for which these three sources differed by <2 K. Both the mean and the standard deviations between calculated and observed sea surface temperature may be considered as being very satisfactory (respectively 0.2 and 1.2 K) since the transformations from METEOSAT to equivalent HIRS/2 observations accounts for a standard deviation of 0.5 K, as explained in Beriot *et al.* (1982).

TABLE 1. Results of the coupling of METEOSAT and TIROS-N sea surface observations corresponding to 23 radiosonde stations on 6, 9, 10, July 1979. (a): date and nearest station; (b) TIROS-N secant; (c) METEOSAT secant; (d) observed SST; (e) extrapolated SST. The mean deviation (Calculated − Observed) is 0.2 K. The standard deviation is 1.2 K.

a	b	c	d	e
6 July 1979				
La Corogne	1.11	1.56	291.2	290.5
Casablanca	1.03	1.28	294.2	293.6
Gibraltar	1.18	1.34	294.2	293.6
Lisbon	1.02	1.41	292.2	292.9
Camborne	1.41	1.86	289.5	287.9
Brest	1.36	1.77	290.2	292.0
Point R	1.01	1.70	290.2	290.3
9 July 1979				
Ajaccio	1.73	1.51	295.2	295.0
La Corogne	1.03	1.56	290.7	289.8
Bordeaux	1.11	1.61	292.4	296.2
Camborne	1.06	1.86	289.2	290.4
Lisbon	1.18	1.41	292.7	294.5
Cagliari	1.96	1.42	295.2	295.8
Point R	1.36	1.70	291.0	292.2
Dar El Beida	1.28	1.36	296.2	295.0
10 July 1979				
Ajaccio	1.62	1.51	295.2	295.5
Bordeaux	1.04	1.61	292.2	292.9
Casablanca	1.62	1.29	295.2	296.0
De Bilt	1.41	1.97	287.2	286.8
Point R	1.48	1.70	291.2	291.9
Shanwell	1.28	2.23	287.2	286.8
Stavanger	1.62	2.54	285.2	283.6
Brest	1.00	1.77	290.2	290.4

3. Synthetic simulation of the double viewing angle method. Case of channel 8 of the HIRS/2 experiment aboard TIROS-N.

Let the upwelling radiance in direction θ and in a spectral region centered at ω be $I(\omega, \theta)$. The radiative transfer equation gives

$$I(\omega, \theta) = B(\omega, T_S)\tau(\omega, \theta, P_S) + \int_{P_S}^{P_0} B(\omega, T)\frac{\partial\tau(\omega, \theta, P)}{\partial \ln P}\, d\ln P, \quad (1)$$

where T is the temperature at pressure level P, $B(\omega, T)$ is the Planck function at wavenumber ω and temperature T, $\tau(\omega, \theta, P)$ is the transmittance between

TABLE 2. Some values taken on by A [Eq. (5)] for a set of 10 atmospheres among the 70 atmospheres (Section 3).

	Total H_2O content	A				Mean A	Standard deviation
		$\sec\theta = 1$	$\sec\theta = 1.2$	$\sec\theta = 1.4$	$\sec\theta = 1.7$		
1	2.0	0.14	0.14	0.17	0.18	0.16	0.02
2	3.4	0.95	0.96	0.95	0.97	0.96	0.01
3	2.5	1.52	1.48	1.47	1.45	1.48	0.03
4	3.4	4.14	3.99	3.84	3.73	3.93	0.18
5	2.0	0.41	0.39	0.37	0.34	0.38	0.03
6	1.7	1.66	1.62	1.57	1.54	1.60	0.05
7	1.8	1.26	1.22	1.19	1.15	1.21	0.05
8	2.1	2.09	2.03	1.97	1.90	1.98	0.06
9	4.0	7.89	7.62	7.34	7.10	7.49	0.34
10	3.0	0.59	0.54	0.47	0.38	0.50	0.09

the satellite and the atmospheric level at pressure P, in the direction θ; and "S" characterizes the surface conditions. The mean value theorem may be used to simplify Eq. (1). Then,

$$I(\omega, \theta) \equiv I_\theta = B(\omega, T_S)\tau(\omega, \theta, P_S) + B(\omega, \bar{T})[1 - \tau(\omega, \theta, P_S)], \quad (2)$$

where $\bar{T}$ represents a mean temperature of the atmosphere between the surface and the highest level where the information comes from. For relatively weak absorption, as occurring in window spectral regions, the transmittance $\tau(\omega, \theta, P_S)$ may be approximated by

$$\tau(\omega, \theta, P_S) \simeq 1 - a \sec\theta + \frac{a^2}{2}(\sec\theta)^2, \quad (3)$$

where a represents all the terms entering the absorption coefficient but $\sec\theta$. Combining Eqs. (2) and (3) leads to

$$I_\theta = B(\omega, T_S) + a[B(\omega, \bar{T}) - B(\omega, T_S)]\left[1 - \frac{a}{2}\sec\theta\right]\sec\theta. \quad (4)$$

From the preceding section, there is an experimental evidence that I_θ is, to a very good approximation, a linear function of $\sec\theta$ with an ordinate at the origin equal to $B(\omega, T_S)$. This fact indicates that, for a given atmosphere, the expression

$$A = a[B(\omega, \bar{T}) - B(\omega, T_S)]\left[1 - \frac{a}{2}\sec\theta\right], \quad (5)$$

is constant, whatever $\sec\theta$ is. In order to ascertain this and also to study the influence of the choice of the viewing angles θ_1 and θ_2 on the accuracy of sea surface temperature determinations, we have carried out synthetic computations simulating a double viewing angle experiment using channel 8 of the HIRS/2 instrument aboard TIROS-N. For that purpose, a set of 70 atmospheric situations were collected, corresponding to clear sky conditions in the Northern Hemisphere (35–55°N), between April and July 1979, with nominal water vapor content varying from 1 to 4.4 precipitable centimeters. The radiances corresponding to these 70 atmospheric situations observed through four directions ($\theta \simeq 0°$, 33°, 45°, 53°) were synthetically generated using the "4A" model described by Scott and Chedin (1981). For these 280 situations, the total transmittance $\tau(\omega, \theta, P_S)$ was thus available, making possible the evaluation of A from Eq. (5). From the analysis of the results, it appears that, for this range of viewing angles ($1 \leqslant \sec\theta \leqslant 1.70$) and for these atmospheres, the mean deviation of A from its mean value is equal to zero with a standard deviation of 0.04 which clearly demonstrates that A, although appearing as the product of two terms which vary with $\sec\theta$, is constant to a very good approximation. Table 2 gives, for a restricted set of 10 atmospheric situations, the values taken on by A for the four secant values considered and a simple statistical analysis of the deviations between A as obtained from Eq. (5) and a constant value. Combining Eqs. (4) and (5) gives

TABLE 3. Surface temperature retrievals using numerical simulations of a double viewing experiment on channel 8 of HIRS/2. The slope of the straight line is that given by Eq. (6).

$\sec\theta_1$	$\sec\theta_2$	$(T_{calc} - T_{obs})$ (K)	Standard deviation (K)
1.02	1.20	−0.4	0.2
1.02	1.42	−0.4	0.2
1.02	1.68	−0.5	0.3
1.20	1.42	−0.5	0.3
1.20	1.68	−0.5	0.3

TABLE 4. Surface temperature retrievals using a double viewing experiment on channel 8 of HIRS/2 for a set containing very humid atmospheres.

$\sec\theta_1$	$\sec\theta_2$	$(T_{calc} - T_{obs})$ (K)	Standard deviation (K)
1.02	1.20	−1.6	1.0
1.02	1.42	−1.7	1.2
1.02	1.68	−1.9	1.4
1.20	1.42	−1.9	1.5
1.20	1.68	−2.0	1.7

$$A = \frac{I_\theta - B(\omega, T_S)}{\sec\theta} = \frac{I_{\theta_1} - I_{\theta_2}}{\sec\theta_1 - \sec\theta_2}. \quad (6)$$

The right-hand-side term is precisely equal to the slope of the straight line joining the two points (I_{θ_1}, $\sec\theta_1$), (I_{θ_2}, $\sec\theta_2$) in the axis system (I_θ, $\sec\theta$). In practice an error is introduced by the fact that Eqs. (4) and (5) strictly hold for one given wavelength (monochromatic case) and do not apply exactly to relatively large spectral intervals. This error acts on the value of A as obtained through Eq. (6) and gives rise to a systematic error in the determination of surface temperatures. This is shown on Table 3 for the set of 70 atmospheric situations mentioned above and for several pairs of values of $\sec\theta$. It may easily be shown that this error increases with atmospheric opacity and we verified this fact using another set of 192 atmospheric situations[1] among which a large number have a very high total water vapor content (up to 7.2 precipitable centimeters for tropical atmospheres). The results are presented in Table 4 for the same pair of secant values. This relatively poor fit is due to the HIRS/2 channel 8 high opacity for such humid atmosphere: e.g., for nadir viewing, the mean transmittance can be as low as 0.3. This can be seen by using a more transparent channel, namely channel 18 of HIRS/2. This channel is centered at 2515 cm^{-1} and is quite sensible to aerosols, thin hazes or sun radiation. The simulation we did ignored these effects. The results are given in Table 5. The agreement is excellent and indicates that a channel more transparent than channel 8 of HIRS/2 has to be found which does not suffer the drawbacks, inherent in channel 18 (near infrared). A good solution would consist in significantly narrowing channel 8 in order to isolate the most transparent part of this spectral region. It is interesting to point out the strong correlation which exists between the total atmospheric water-vapor content and the differences between the retrieved values of the surface temperature and the correct values. This correlation is illustrated in Fig. 4 where these differences are plotted against the water-vapor content for the set of humid atmospheres. Coupling a geostationary satellite like METEOSAT with a satellite of the TIROS-N series allows the major part of such errors to be corrected by using the information coming from the water-vapor channels of HIRS/2. This is *a fortiori* true for the GOES series equipped with the VAS (Vertical Atmospheric Sounder) experiment.

[1] This set has been extracted from a larger set provided to us by NESS (National Earth Satellite Service), Washington.

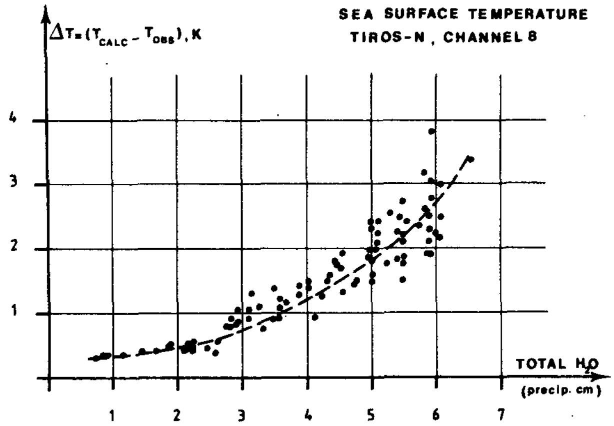

FIG. 4. Deviations between retrieved and true surface temperatures plotted against the total water vapor content for a set containing very humid atmospheres in the case of a simulated double viewing angle experiment in Channel 8, TIROS-N HIRS/2 radiometer.

4. Influence of the viewing angles on the accuracy of retrieved temperatures

Although Tables 3–5 indicate a variation of the agreement between retrieved and true surface temperatures with respect to the two viewing angles selected, it is obvious that no definite conclusion can be obtained without superimposing to the synthetic radiant energies, computed for each angle, a random error normally distributed and with a standard deviation close to that of the instrument itself (here, channel 8 of HIRS/2). This numerical simulation was done for the set of 70 atmospheric situations briefly described in the preceding section. The standard deviation of the errors added to synthetic radiances was taken equal to 0.15%. The results are presented in Table 6 and indicate that the best so-

TABLE 5. Surface temperature retrievals using a double viewing experiment on channel 18 of HIRS/2 for a set containing very humid atmospheres.

$\sec\theta_1$	$\sec\theta_2$	$\overline{(T_{calc} - T_{obs})}$ (K)	Standard deviation (K)
1.02	1.20	0.1	0.02
1.02	1.42	0.1	0.01
1.02	1.68	0.1	0.02
1.20	1.42	0.1	0.02
1.20	1.68	0.1	0.02

TABLE 6. Influence of the viewing angles on the quality of temperature retrievals. Random errors (normal distribution; standard deviation equal to 0.15%) have been added to synthetic data used in Table 3.

$\sec\theta_1$	$\sec\theta_2$	$\overline{(T_{calc} - T_{obs})}$ (K)	Standard deviation (K)
1.02	1.20	−0.3	0.9
1.02	1.42	−0.4	0.6
1.02	1.68	−0.4	0.4
1.20	1.42	−0.6	1.2
1.20	1.68	−0.5	0.7

lution is between the second and the third couple of angles ($\sec\theta_1 \simeq 1$ and $1.4 \leqslant \sec\theta_2 \leqslant 1.7$). However, one must not forget that, for these numerical simulations, it is assumed that the atmospheric conditions met along the two paths are identical, which is not exactly the real case.

5. Conclusion

Coupling observations made simultaneously by a geostationary satellite and by a polar orbiting satellite of the TIROS-N series makes it possible to experimentally simulate a double viewing angle experiment aiming at the remote determination of sea-surface temperature. That way of obtaining different amounts of atmospheric absorptions has an important advantage over the more usual way which consists in varying the wavelength. This advantage comes from the fact that the spectroscopic aspect of the problem has been almost completely eliminated. Indeed, the "anomalous" (or unknown) spectroscopic behavior of some of the components of the total absorption is still a source of trouble in a wavelength differential approach. The preliminary experimental test of a double viewing experiment, simulated using METEOSAT and TIROS-N, presented in this paper has demonstrated the quality of the method: the mean and the standard deviations between retrieved and observed surface temperatures are, respectively, 0.2 and 1.2 K, the latter number being affected by the transformation of METEOSAT observations into equivalent TIROS-N observations (standard deviation 0.5 K). The drawback of the method is the added complexity of the spacecraft sensor system. It is however our feeling that the double angle viewing technique is very promising and will find other important applications (see Fleming, 1980) like a better determination of "cloud-free" radiances from cloud-contaminated observations.

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