Linearity of the (A)ATSR LST Algorithm

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In some research studies of land surface temperature derivation from satellites, it has been suggested that there is a significant non-linear effect in the dependence of the brightness temperature difference (T_{11}-T_{12}) with ground temperature. Although there seems scant observational evidence for this and the theoretical justification is lacking, it seems relevant to investigate the validity of the claims. Here ground validation data from the Australian validation sites at Hay, NSW and Walpeup, Victoria are used together with coincident ATSR/ATSR-2 measurements to investigate the non-linearity effect. These data are arguably the most complete and accurate land surface temperature data currently available, and span a range of temperatures from 270 K to 330 K. No evidence is found for a significant non-linearity, the root-mean-square errors for the entire data set are ±4.49 K for a linear fit and ±4.50 for a quadratic fit. Furthermore, the non-linear effect only becomes apparent at quite high temperatures (Ts>320 K), and since the ATSR-2 11 μm channel saturates at about this temperature, the idea of using a questionable non-linear term is moot.

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1 Background

Recent papers by Coll and Caselles (1997), Galve et al. (2005) and the work of Noyes (2007) suggest that some improvement in the accuracy of land surface temperature might be obtained by including a second order term for the dependence on brightness temperature difference ($\Delta T = T_{11} - T_{12}$). The general form may be written:

$$LST = a_0 + a_1(T_{11} - T_{12}) + a_2(T_{11} - T_{12})^2$$

where a_0, a_1 and a_2 are coefficients that may or may not depend on land type, land cover, and water vapour.

The rationale for including the quadratic term seems to be that as water vapour amount increases the difference between the sensed temperature (e.g. T_{11}) becomes significantly different from the actual surface temperature. In this case many of the underlying assumptions of the derivation of the LST break-down. One assumption used is that the air temperature and the surface temperature must not be too different. When there is a lot of water vapour the centre of mass of the T_{11} measurement rises and becomes depressed compared to the surface temperature. Since the 12 μm channel is more affected by water vapour than the 11 μm channel, its depression is greater and the difference between the two channel measurements increases. Temperature and water vapour are related in a non-linear manner; this can be anticipated from the variation of saturation vapour pressure of water vapour with air temperature, through the Clausius-Clapeyron relation.

Since satellites don't measure thermodynamic temperature, a further approximation must be made that essentially relies on the surface and air temperatures being "not too different". Given that there may be many circumstances when these assumptions breakdown, the approximation of linearity may be suspect. Nevertheless, it the linearity assumption has proved very successful over the oceans, where the air and surface temperatures are seldom very different and large water vapour amounts rare. At high viewing angles the water vapour path amount (the product of the water vapour concentration and the pathlength) can be and nonlinear effects have been noticed. Introducing a second order term for SST derivation seems to produce better retrievals, so it is relevant to question whether the same may be true over the land.

Over the land surface there is a further complication because ΔT is also affected by the emissivity difference at T_{11} and T_{12}, which is non-zero. Thus, although it would seem reasonable to include a second order correction term of the form ΔT^2 for the atmospheric effect (water vapour), this may not be advisable, or more accurate for the surface effect (emissivity).

2. Validation data

In order to properly test the idea of using a non-linear term in the LST algorithm it is necessary to utilize accurate land surface temperature validation data. Moreover, the data must span a wide range of temperatures and also a wide range of water vapour loadings. Before the validation data are introduced it is important to list a few pertinent points:

1. The non-linear effect happens when there are high water vapour amounts.
2. When the water vapour loading is high the measured signal comes more from the atmosphere than the surface, effectively decoupling the surface from the atmosphere.
3. The non-linear effect is largest when the difference between the surface temperature, Ts and the 11 μm brightness temperature is largest. In fact this difference needs to be > 10 K before any effect is noticed.
4. To get such large differences over the land surface, the actual surface temperature must be quite high (since water vapour and temperature are related in a non-linear way– when the water vapour is high the air temperature must be high too).
5. Unlike the ocean, the land surface can be naturally heated to extremely high temperatures (>330 K), causing temperature differences between the land surface and the air temperature to be as large as 20 K, without any significant water vapour loading.
6. At high water vapour loadings, mostly observed in the tropics, the air quickly becomes saturated and clouds form. Thus at the highest water vapour loadings it is actually quite difficult to get clear sky satellite measurements.
7. Above about 320 K, the ATSR and ATSR-2 11 and 12 μm channels saturate (see Prata, 2000). Thus when there is a large difference between the surface temperature and the 11 μm temperature, the channel may well be saturated.
8. Large temperature differences between the 11 and 12 μm temperatures suggest large water vapour loadings over the ocean. Over the land, for the same water vapour loading, the spectral emissivity of the land could enhance, lower or have no effect on the difference, depending on the nature of the surface. This suggests immediately that any algorithm that includes a non-linear term must also include a land surface dependent coefficient.

With these points in mind and given that accurate land surface temperature validation data are quite rare, the Australian validation data from the Hay and Walpeup sites are used. These data are described in Prata (1994) and were specifically collected with satellite validation in mind. The data have been used in numerous studies and it is generally agreed that these data are accurate and suitable for validation at 1 km^2 scales. All the details of these data are described in Prata (1994a), and have been utilized in the studies by Prata (1993), Prata (1994b), Sobrino et al. (1999), and Coll et al. (2000), amongst others.

3. Analyses

The purpose of this study is simply to identify whether there is any sense in including a non-linear term in the LST algorithm. Within the data set there are 282 clear-sky, day and night surface temperatures, and ATSR T_{11} and T_{12} brightness temperature measurements. The temperature range is from about 270 K to about 326 K. Independent water vapour measurements are not available for these data, but this does not matter as the algorithm is supposed to account for this. What is more important is the existence of data with T_s–T_{11} > 2–10 K. In fact the water vapour laodings for these sites generally does not exceed 40 kgm^{-2}, so it is likely that most of the difference is simply due to solar heating of the surface, causing a large surface to air temperature differential.

Figure 1 shows a plot of the ground surface temperature and the temperature depression (T_s-T_{11}) for all of the 282 data points. It can be seen that there are many points with T_s-T_{11}> 5 K and about 8 values with T_s-T_{11} > 10 K. Despite surface temperatures exceeding 320 K (47 ºC), there are no differentials as high as 20 K. Linear regression and polynomial fits to these data sets show no significant difference. The rms errors for the linear fit is ±4.49 K, while for the degree-2 polynomial fit it is ±4.50 K. The difference between these is not significant. The fits are also shown on the Figure: the red-coloured line is the linear fit and the green-coloured line is the degree-2 polynomial. The vertical dashed line represents the ATSR 11 μm brightness temperature saturation. This data-set suggests there is no justification for using a polynomial fit, although such a fit does not degrade the relation in a significant way.

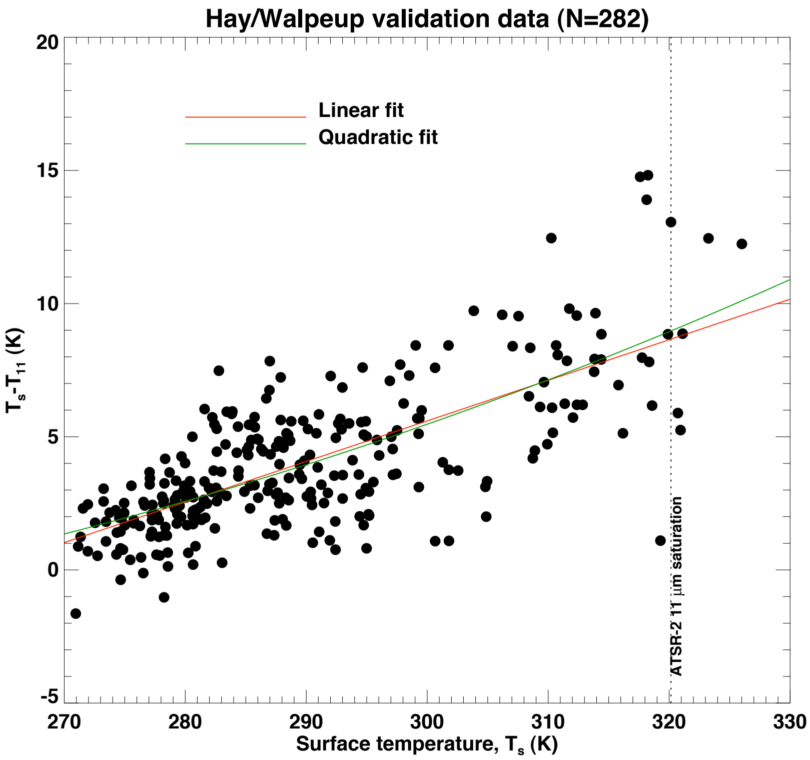

Figure 1. Plot of the measured ("ground truth") surface temperature and the temperature depression (surface temperature – 11 μm brightness temperature) for 282 data points obtained over the Australian Hay and Walpeup validation sites.

Perhaps it is more instructive to investigate whether an algorithm with a non-linear dependence out performs the usual linear algorithm. Without prejudice the algorithm of Galve et al was selected for this comparison. The algorithm may be written:

$$LST = T_{11} + 0.024 + 0.782(T_{11} - T_{12}) + 0.302(T_{11} - T_{12})^2 + (1-\varepsilon)f(pw) - \Delta\varepsilon g(pw)$$

where e is the T_{11} emissivity, De is the spectral emissivity difference and f(pw) and g(pw) are functions that depend on water vapour. An interesting aspect of this algorithm is that when $T_{11}<T_{12}$, the quadratic term introduces an additive effect to the algorithm, which is fundamentally incorrect. Negative brightness temperature differences occur frequently over the land, due to temperature and moisture inversions (Platt and Prata, 1990). Of course this effect can be cancelled out by making $\Delta\varepsilon$ sufficiently positive. Essentially algorithms of this kind can be constructed in an infinite number of ways as longs as the 1st three terms remain. These are the terms that account for 90% or more of the variation. To demonstrate this, the LST for all 282 validation points is calculated by assuming that ε=1 and $\Delta\varepsilon$=0. This is repeated by ignoring the quadratic term and altering the linear coefficient to have a value of 2.8 instead of 0.782, so that a linear form of the algorithm =can be tested. The results are shown in Figure 2.

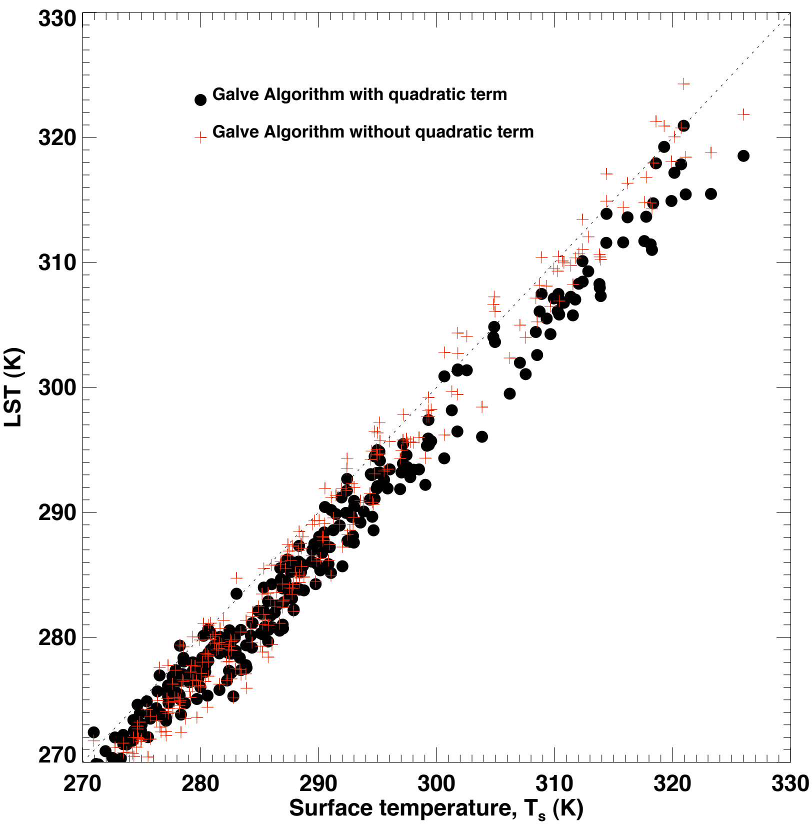

Figure 2. "Ground truth" surface temperatures and LSTs derived from an algorithm with (black dots), and without (red crosses) a quadratic term. It turns out that the linear form has about ±0.5 K lower rms error for this particular set of data.

It can be seen that there is no difference between the results. In fact the rms errors between the each algorithm and the ground data are ±3.56 K for the non-linear algorithm and ±3.08 K for the artificial linear algorithm. No claim in improved accuracy is being made by using the linear algorithm, as the emissivity and precipitable water terms have been ignored. However, it should be apparent that the algorithm can be manipulated in a variety of ways to optimize it for this data set. The Galve algorithm was determined through radiative transfer simulations and so its behaviour is model dependent and has little observational constraint.

4. Conclusion

This study has used an accurate set of land surface validation data to investigate whether there is a significant non-linear correction term required for satellite-based LST algorithm development. The results do not support the introduction of a non-linear term, although for these data (bare and grass-covered surfaces), its introduction does not degrade the results. By comparing a linear and non-linear LST algorithm, it is shown that there is no justification for using a non-linear algorithm and it is argued that the form may not be physically realistic for some land surfaces. Invoking arguments based on the use of non-linear terms for SST determination cannot be sustained because of the different physical processes that occur at the sea-air and land-air interfaces. The thermal character of soil and water are different; the land surface can be quickly heated, whereas the sea surface cannot (in general) and hence a large temperature differential between the surface and air can be established for the land, but rarely for the ocean. Ocean surfaces rarely exceed 35 ºC, whereas the land surface can reach twice this value–the theoretical maximum land surface temperature has been estimated as 90–100 ºC by Garratt (1992).

The ATSR/ATSR-2/AATSR algorithm was developed from careful studies using observational data gathered over a period of 10 years and supplemented by theoretical analyses. Many researchers are now using "simulated observations" based on radiative transfer modeling to develop relationships between land surface emissivity, precipitable water, viewing geometry, air temperature, satellite measurements and land surface temperature. It is essential to keep in mind that these models are only an approximation to the real world and often do not account for many of the important (complex) processes that the real world contains.

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5 References

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