# A Summary of MTP Results for TORERO

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Revised July 2024 (Originally released July 16, 2012)

## Introduction

We summarize the results of the analysis of the Microwave Temperature Profiler (MTP) data obtained on the NSF/NCAR GV (NGV) during the TORERO field campaign. Its purpose is two-fold: to present the final MTP data with comments on each flight, and to discuss the excellent temperature calibration that was achieved. This document can be found under 'Documentation' in the data archive for the TORERO MTP dataset so that users can obtain a summary of data quality and interesting features associated with each flight. Following this summary, we provide information on how the aircraft in situ temperature was verified against radiosonde data prior to its use for MTP calibration. Following these comments, we provide information on how the temperature was calibrated (very successfully) for the TORERO campaign.

## 1 Results

### Comments on the TORERO MTP Final Data

Color-coded temperature curtain (CTC) plots are available for each of the MPEX research flights with comments which include summaries of each flight. These comments may indicate areas of reduced data quality and/or significant features noted in the temperature profiles.

First we provide an elaboration on the impact of rapid ascents and descents on the quality of the MTP retrievals. When retrievals are performed, the retrieval coefficients that we use assume that the pressure altitude is approximately constant. Clearly over a ~20 second MTP scan, this is not the case if the GV is profiling. Given a typical ascent or descent rate of ~150 m/s, 3 km are traversed in the vertical. (The actual distance is more like 2 km because not all of the 20 seconds is needed for measurements, but this is still unacceptably large.) We have tried to save as much of the ascent and descent data as possible by changing the editing threshold when it appears that the retrievals are consistent with the short level flight segments. This can be done by examining the behavior of the tropopause or the temperature field retrievals during ascent or descent compared to those during the level flight segments.

On each of the following CTC plots the x-axis is the Universal Time (UT) in kilo-seconds (ks), the left y-axis is the pressure altitude in kilometers (km), and the right y-axis is the pressure altitude in thousands of feet (kft). On the right is the color-coded temperature scale, which ranges from 170- 320 K. Also shown on each plot is the GV's altitude (black trace), the tropopause altitude (white trace), and a quality metric (gray trace at the bottom). The quality metric, which we call the MRI, ranges from 0 to 2 on the left pressure altitude scale. If the MRI is $< 1$, we consider the retrieval to be reliable; if it is $> 1$ the retrieval is less reliable, and users should contact us as to whether it can be used or not. The MTP final data have been edited to include retrievals with the MRI $< 0.8$. If this excludes a specific time period that someone is interested in, they should contact us to see whether we can salvage that time period. The CTC plots are generally restricted to ± 8 km from flight level. On a few flights this was increased so that higher tropopauses could be plotted; this was the case for several tropical flights.

## 1.1 FF01: Ferry flight to San Jose, Costa Rica

The retrievals before 62 ks could use better retrieval coefficients. Because this was a ferry flight, time was not taken to improve these retrievals. A jump from a mid-latitude tropopause (~12 km) to a tropical tropopause (~17 km) occurred at ~66 ks.(Figure 1).

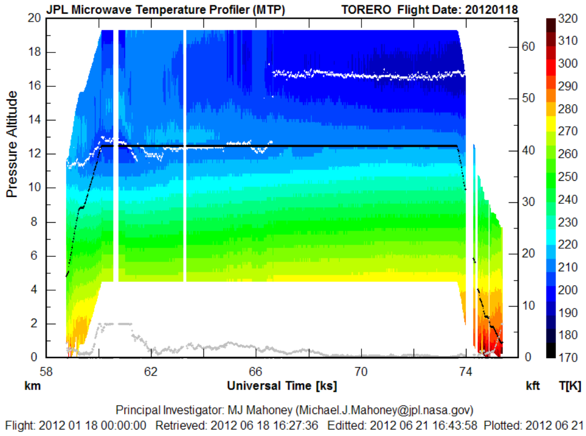


Figure 1: CTC Plot from Ferry Flight 1 on January 18, 2012

## 1.2 RF01: Research flight from San Jose, Costa Rica, to Antofagasta, Chile

The MTP was not started correctly on this flight resulting in random scan lengths. The data could not be processed.

## 1.3 RF02: Local flight from Antofagasta, Chile (southward)

There were double tropopauses on this flight up to ~68 ks (~11 km and 16 km. The retrievals are good but are a bit degraded for a short period at ~61 ks.

For all the Antofagasta flights the low altitude retrievals should not be trusted because we did not do the extra work needed to handle surface emissivity issues when looking down, and because the only available Antofagasta soundings were not launched at the flight time (and therefore were isothermal below ~4 km instead of much warmer) (Figure 2)

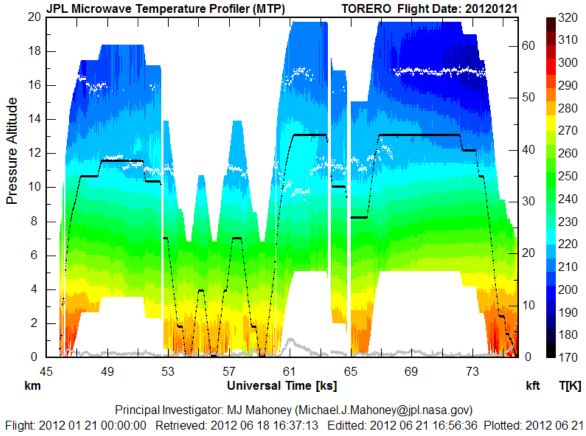


Figure 2: CTC Plot from Research Flight 2 on January 21, 2012

## 1.4 RF03: Local flight from Antofagasta, Chile (westward)

The data for this flight looks excellent.

The trops are tropical (~16 km) except from ~55 ks to 68 ks when double trops appear to occur (Figure 3).

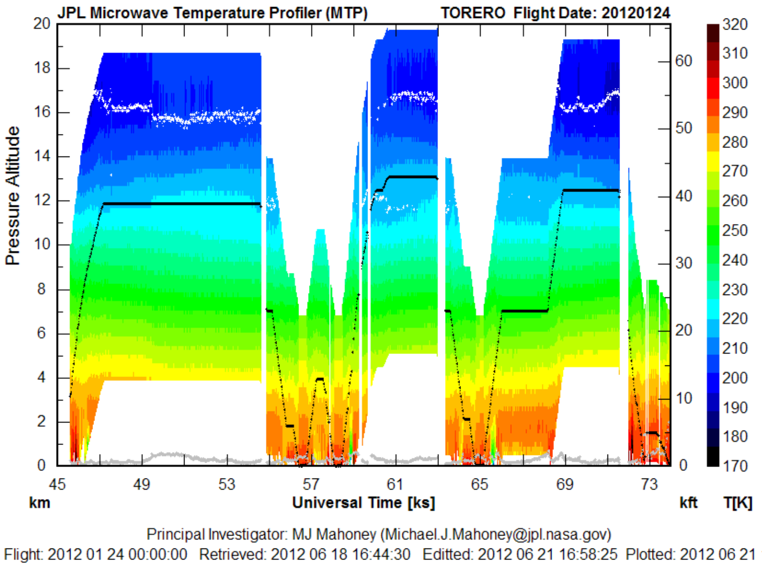


Figure 3: CTC Plot from Research Flight 3 on January 24, 2012

## 1.5 RF04: Local flight from Antofagasta, Chile (southward)

This flight looks very good. except for a short period at ~61 ks.

The trops are tropical (~16-17 km) except from ~51 ks to 62 ks when double trops appear to occur. (Figure 4).

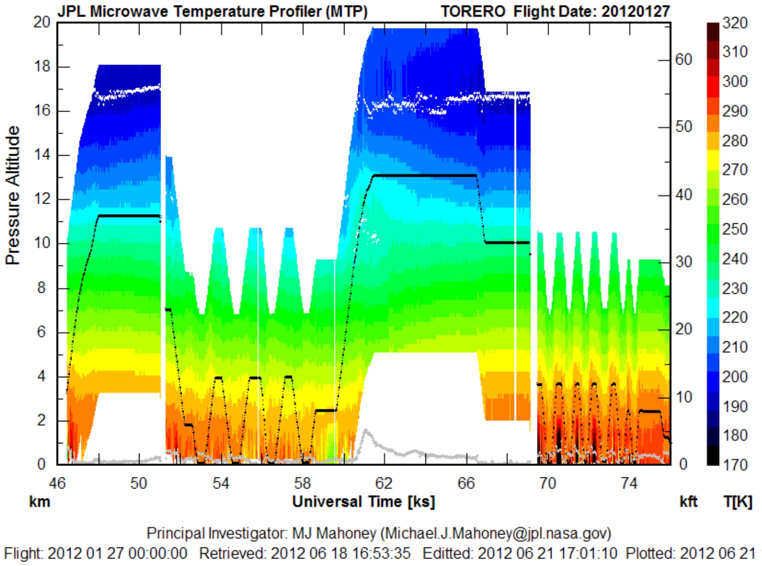
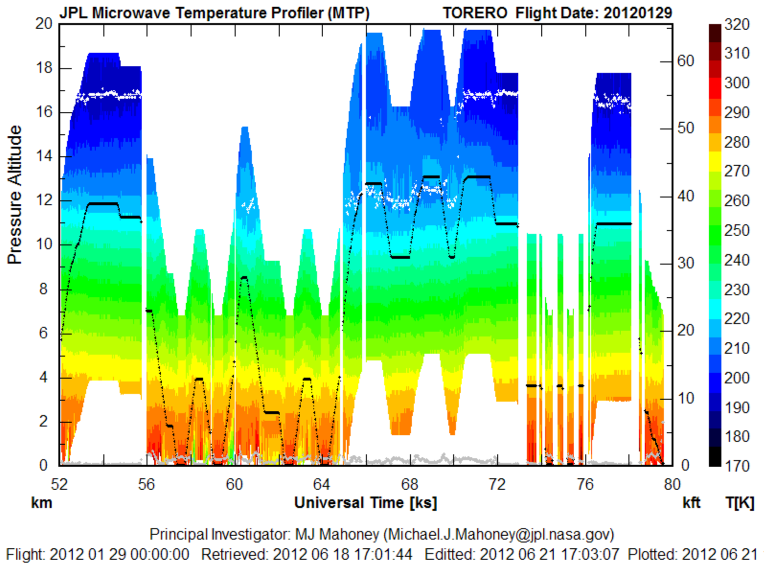


Figure 4: CTC Plot from Research Flight 4 on January 27, 2012

## 1.6 RF05: Local flight from Antofagasta, Chile (westward)

The retrieval for this flight look very good.

The trops are tropical (~16-17 km) except from ~50 ks to 70 ks when double trops appear to occur.(Figure 5).



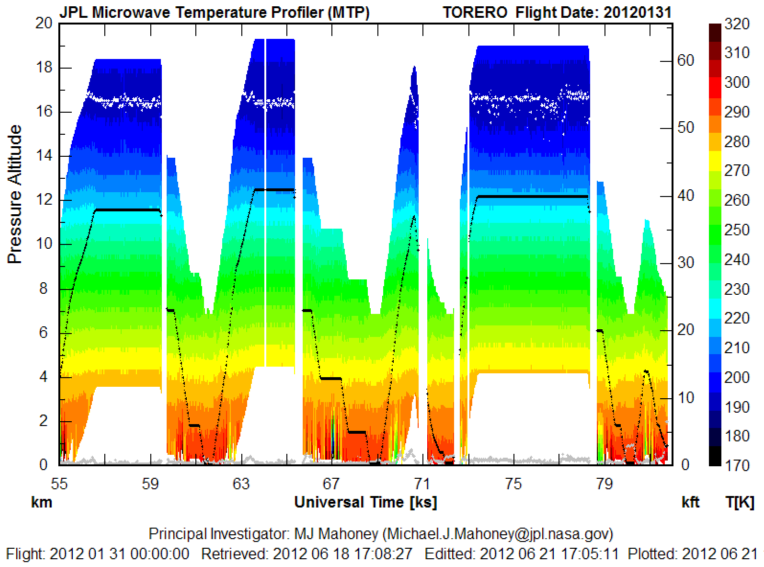
Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 01 29 00:00:00 Retrieved: 2012 06 18 17:01:44 Editted: 2012 06 21 17:03:07 Plotted: 2012 06 21

Figure 5: CTC Plot from Research Flight 5 on January 29, 2012

## 1.7 RF06: Research flight from Antofagasta, Chile, to San Jose, Costa Rica

The data for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k) (Figure 6).



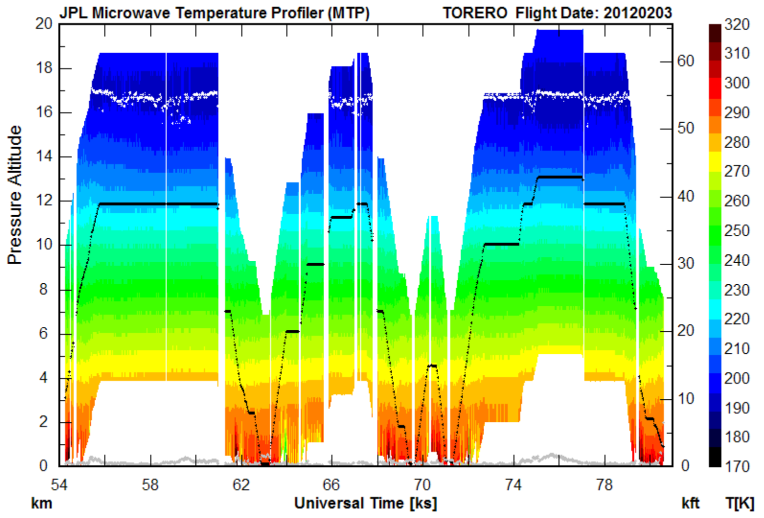
Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 01 31 00:00:00 Retrieved: 2012 06 18 17:08:27 Editted: 2012 06 21 17:05:11 Plotted: 2012 06 21

Figure 6: CTC Plot from Research Flight 6 on January 31, 2012

## 1.8 RF07: Research flight from San Jose, Costa Rica (southwest)

Research flight from BJC covering areas of Kansas, Nebraska, Colorado, Utah, and New Mexico

The data for this flight look excellent. Double tropopauses persist throughout, with some uncertainty in the upper tropopause height early in the flight.(Figure 7).



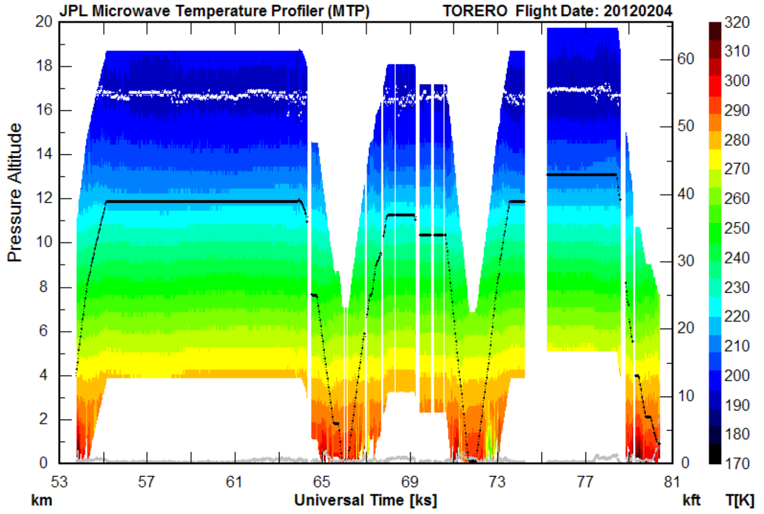
Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 02 03 00:00:00 Retrieved: 2012 06 18 17:15:17 Editted: 2012 06 21 17:07:12 Plotted: 2012 06 21

Figure 7: CTC Plot from Research Flight 7 on February 3, 2012

## 1.9 RF08: Research flight from San Jose, Costa Rica (southwest)

The data for this flight looks excellent.

The tropopause is tropical for the entire flight (~16-17 k) (Figure 8).



Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 02 04 00:00:00 Retrieved: 2012 06 18 17:22:32 Editted: 2012 06 21 17:11:44 Plotted: 2012 06 21

Figure 8: CTC Plot from Research Flight 8 on February 4, 2012

## 1.10 RF09: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k)(Figure 9).

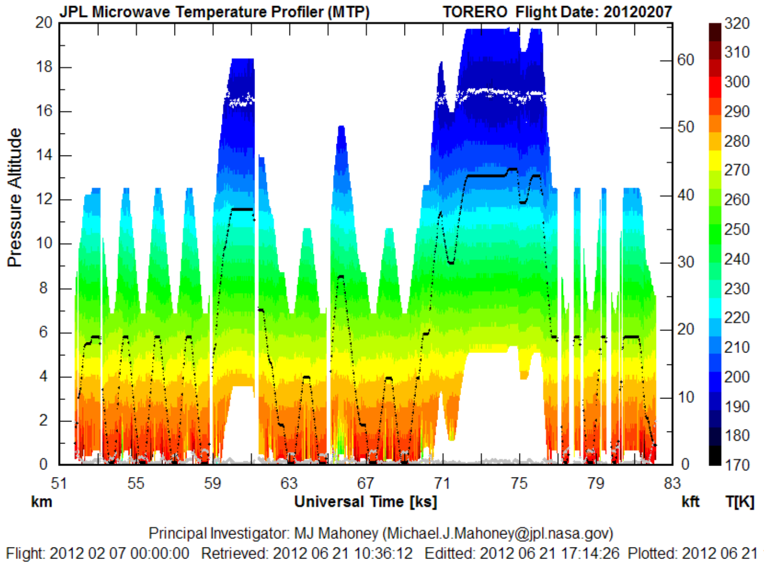


Figure 9: CTC Plot from Research Flight 9 on February 7, 2012

## 1.11 RF10: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k) (Figure 10).

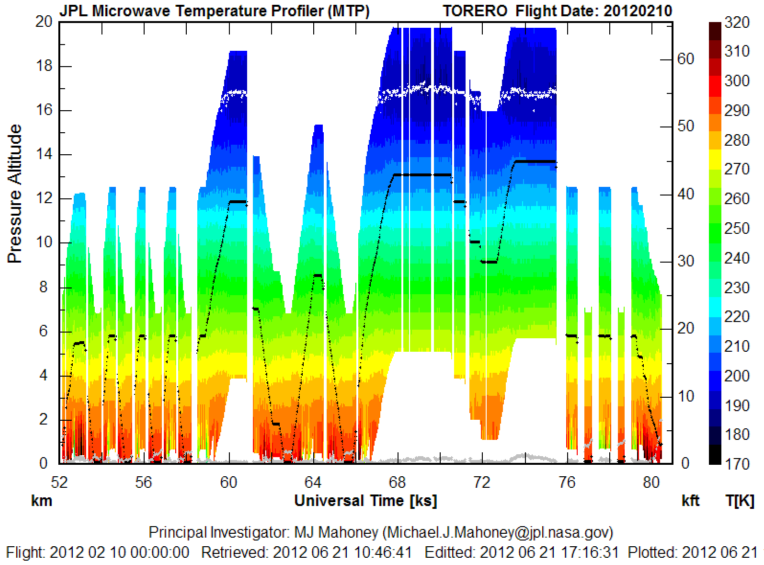


Figure 10: CTC Plot from Research Flight 10 on February 10, 2012

### 1.12 RF11: Research flight from San Jose, Costa Rica (northwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k)(Figure 11).

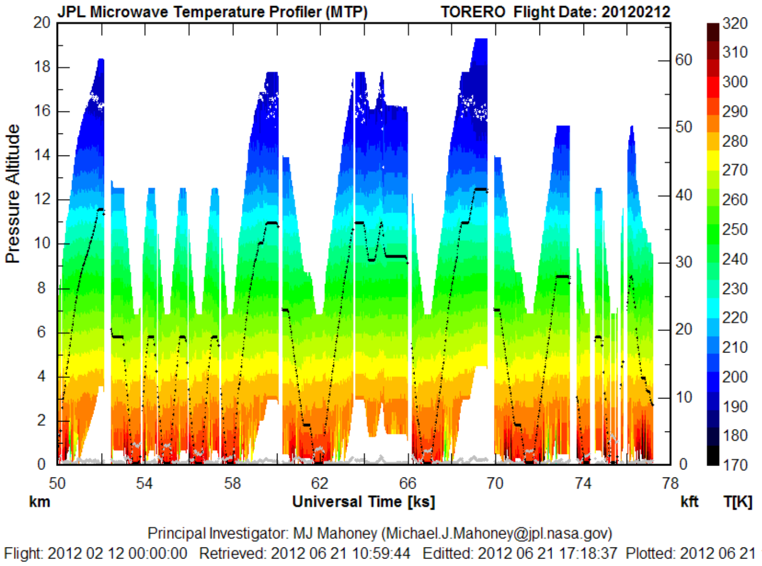


Figure 11: CTC Plot from Research Flight 11 on February 12, 2012

### 1.13 RF12: Research flight from San Jose, Costa Rica (west)

The retrievals for this flight generally look good. Temperature variability associated with the upper-tropospheric trough/jet is evident (Figure 12).

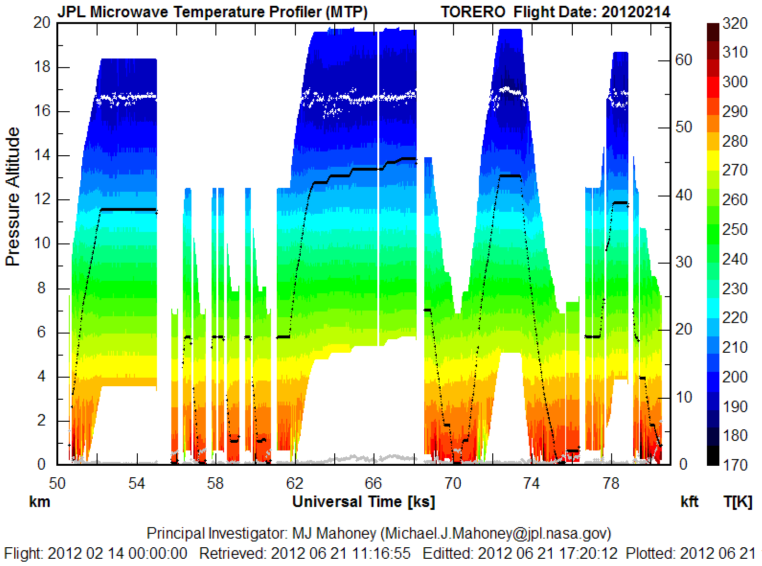


Figure 12: CTC Plot from Research Flight 12 on February 14, 2012

## 1.14 RF13: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k)(Figure 13).

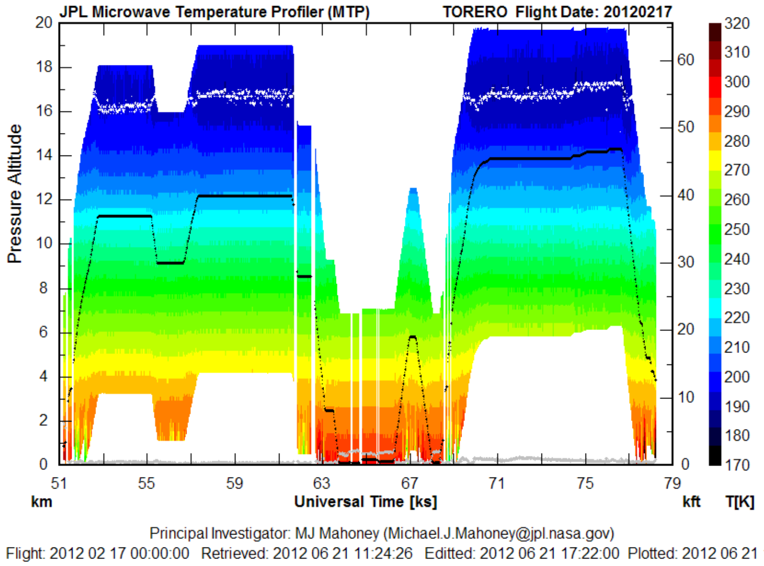


Figure 13: CTC Plot from Research Flight 13 on February 17, 2012

## 1.15 RF14: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k)(Figure 14).

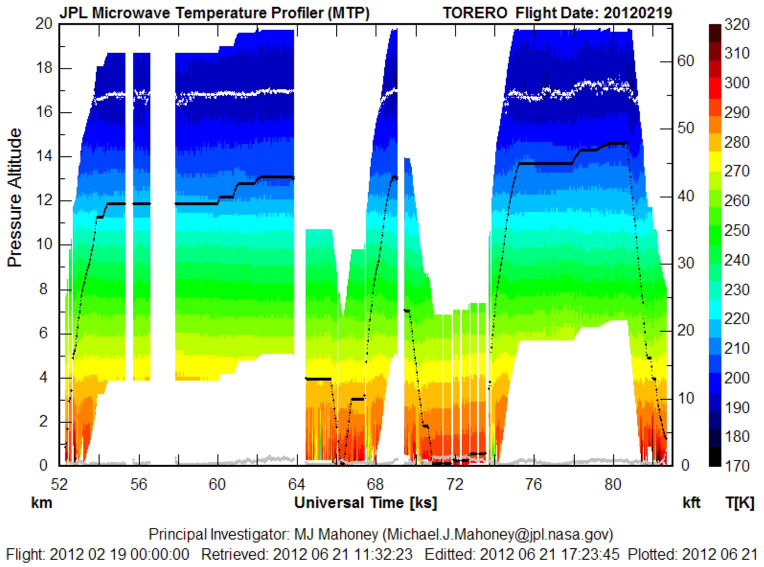


Figure 14: CTC Plot from Research Flight 14 on February 19, 2012

## 1.16 RF15: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent (Figure 15).

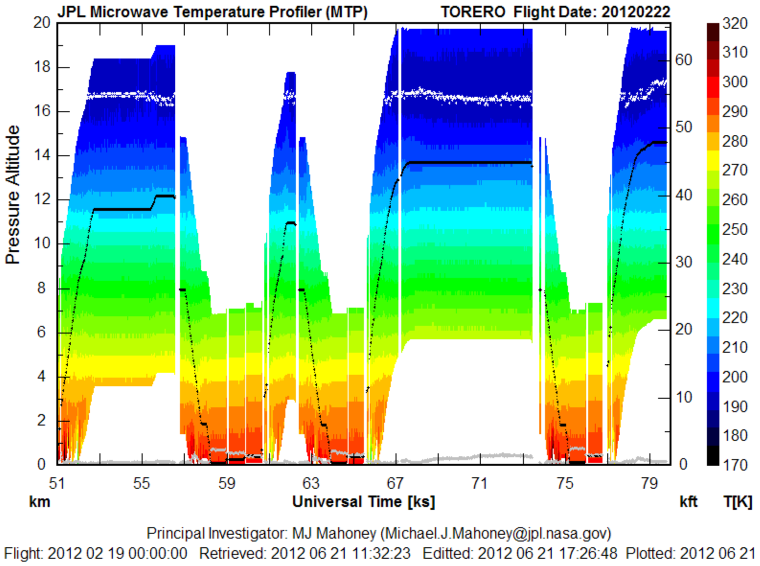


Figure 15: CTC Plot from Research Flight 15 on February 22, 2012

## 1.17 RF16: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k)(Figure 16).

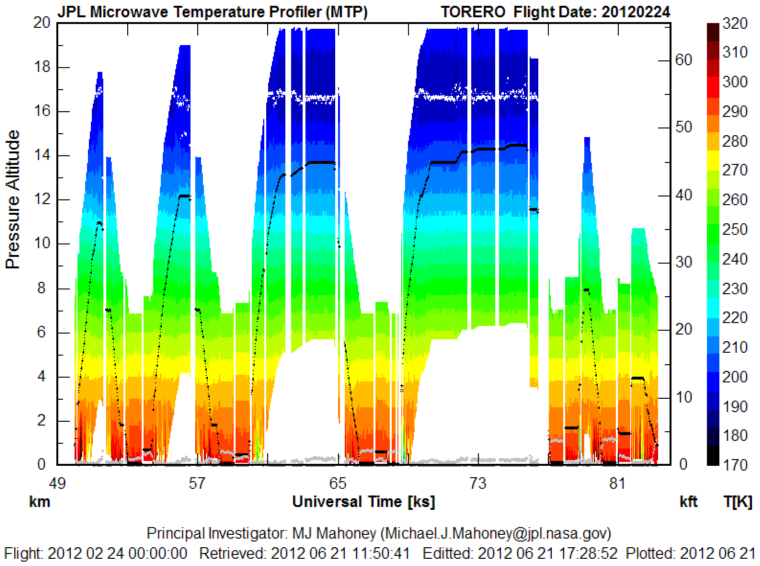
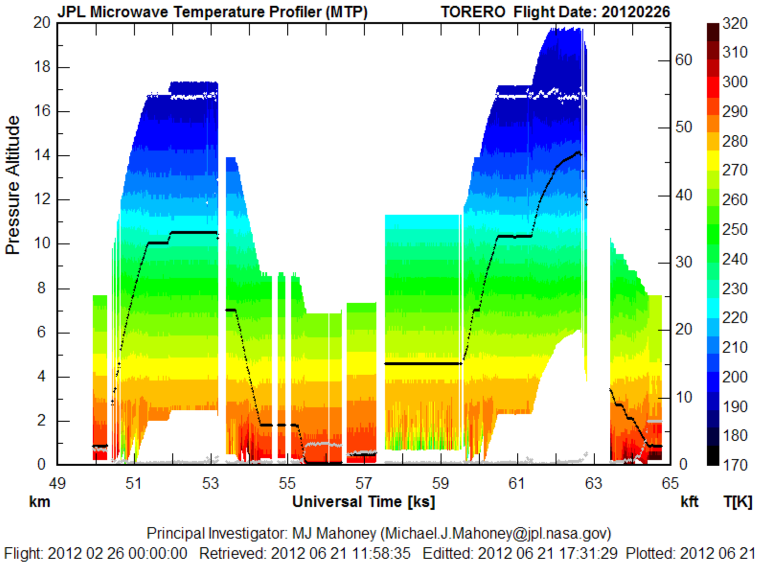


Figure 16: CTC Plot from Research Flight 16 on February 24, 2012

## 1.18 RF17: Research flight from San Jose, Costa Rica (southwest)

The retrievals for this flight look excellent.

The tropopause is tropical for the entire flight (~16-17 k) (Figure 17).



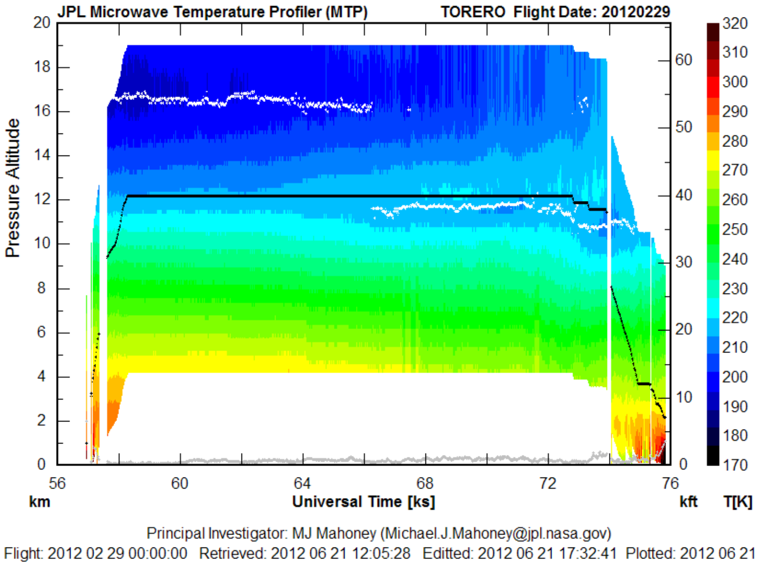
Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 02 26 00:00:00 Retrieved: 2012 06 21 11:58:35 Editted: 2012 06 21 17:31:29 Plotted: 2012 06 21

Figure 17: CTC Plot from Research Flight 17 on February 26, 2012

## 1.19 FF02: Ferry flight from San Jose, Costa Rica, to RMMA

The retrievals for this flight look excellent.

The tropopause is tropical (~16.5 k) until ~66 ks, then it becomes mid-latitude (~11 km) with occasional double trops.(Figure 18).



Principal Investigator: MJ Mahoney (Michael.J.Mahoney@jpl.nasa.gov)
Flight: 2012 02 29 00:00:00 Retrieved: 2012 06 21 12:05:28 Editted: 2012 06 21 17:32:41 Plotted: 2012 06 21

Figure 18: CTC Plot from Research Flight 17 on February 29, 2012

# 2 TORERO Temperature Calibration

## 2.1 Background

For more than two decades the MTP team has been refining techniques for calibrating *in situ* temperature measurements made aboard research aircraft by performing comparisons with radiosondes launched near the aircraft's flight track. Initially this was done by hand, and could involve as much as a day for a single comparison because of the tedious quality control procedures that had to be implemented (such as limiting pressure altitude excursions during the comparisons, restricting allowable pitch and roll changes, and checking for radiosonde temporal and spatial variability). About a decade ago these procedures were largely automated, but the comparisons were made for the entire MTP-retrieved temperature profile at that time, not just at flight level.

Even though the MTP did not participate in the T-Rex campaign, we were asked if the MTP temperature calibration techniques could be applied to the the research and avionics temperatures measured during T-Rex so that differences in these temperatures could be resolved. During T-Rex the GV flew from RMMA to near Independence, CA, where it spent most of its flight time. In addition to the NWS soundings on transit, Leeds University frequently launched radiosondes from Independence, CA (INCA), so we had a wealth of soundings with which to do comparisons. All of the radiosondes used had an accuracy of ±0.3 K. As described on another web page, we found that both the research temperature Tres (ATRL) and the avionics temperature Tavi (AT_A) had substantial warm biases with respect to radiosondes launched near the GV flight track ($Tavi - Traob = 1.21 \pm 0.12$, and $Tres - Traob = 2.37 \pm 0.12$, respectively). While Tres has the largest warm bias, we also found that the Tavi warm bias is very significantly pressure altitude dependent.

This work to understand the T-Rex *in situ* temperatures opened the door to a new approach for doing the MTP temperature calibration. As mentioned above we had previously compared the entire retrieved temperature profile to radiosondes, not just the flight level temperature. This often required several retrieval iterations through all the flights to achieve acceptable results. After doing the T-Rex comparisons, it was realized that, if the flight level temperature was calibrated independently of the MTP data, less work would be needed. (This is the case because previously we applied a correction to the in situ temperature measurement called OATnavCOR. Therefore, every time that OATnavCOR changed we would have to recalculate the instrument gain. If the flight level temperature is accurately calibrated from the start, then OATnavCOR is always 0.0 K, and the instrument gains do not have to be recalculated. This saves a lot of effort.)

We have continued to refine the temperature calibration techniques that we developed for T-Rex on subsequent GV campaigns. Other documents that describe this procedure can be found under 'Documentation' in the following data archives: START-08, T-REX HIPPO-1, HIPPO-2, HIPPO-3, PREDICT, HIPPO-4, HIPPO-5, and DC3-TEST.

Before discussing the calibration procedure for the TORERO field campaign, we will first provide a little background. During the HIPPO field campaigns the GV was for the most part continuously profiling the troposphere (and sometimes the lower stratosphere). This was a significant concern for a number of reasons:

- First, in order to obtain good temperature profile retrievals, the MTP requires that the pressure altitude of the aircraft be relatively constant during the course of a ~20 second scan. This was blatantly not the case when the GV is behaving like an over-sized atmospheric yo-yo.
- Second, related to this is the fact that we have typically averaged 3-7 scans to beat down noise introduced by mesoscale temperature variations. Such averaging would be impossible during rapid descents and ascents.
- Third, in the past we have flatly refused to do radiosonde comparisons in the troposphere because of the high lapse rate, and therefore sensitivity to altitude excursions.
- Fourth, in order to do radiosondes comparisons, you need radiosondes. Since most of the HIPPO flights were in radiosonde sparse regions (the Arctic, Antarctic and Pacific Ocean), obtaining enough comparisons to achieve good statistics could be difficult.
- Fifth, careful consideration needs to be given to the dependence of the temperature recovery factor on Mach Number. There is no way that a constant temperature recovery factor can be used when an aircraft (and its in situ temperature probes) are profiling the atmosphere.

For these reasons our hand was forced. Normally when we do radiosonde comparisons, we do them at the time of great-circle closest approach to the radiosonde launch site. We are also careful to make sure that no one radiosonde comparison overly weights the statistics. For example, suppose that the GV was taking off or landing at an airfield where radiosondes were launched. The "closest approach" algorithm might produce multiple times of closest approach during frequent turns. We would edit out these additional comparisons to avoid overly weighting the statistics to this site. Given the sparsity of oceanic and polar radiosondes, and the desire to have good statistics, we decided to try a new approach for the HIPPO campaigns (and other campaigns where atmospheric profiling is common, including during TORERO). Instead of using the great-circle time of closest approach to make the comparison, we decided to do comparisons every 1 km in altitude from 2 km on up with the closest radiosonde launch site that was available. (If the closest radiosonde launch site was very distant, we had a filter that would exclude soundings beyond a specified distance threshold.) This approach would increase the number of potential comparisons by nearly an order of magnitude. But equally as important, it would allow us to assess whether any of the *in situ* temperature measurements had a pressure altitude dependence, which, as we remarked above, was the case for the avionics temperature during T-Rex. In addition to allowing tropospheric radiosonde comparisons, we would also be forced to abandon averaging of scans to beat down the mesoscale temperature noise, since (when profiling) the temperature change due to altitude change completely dominates any change due to mesoscale temperature variations.

## 2.2 TORERO Specifics

There were a number of new hoops that had to be jumped through for TORERO because of the lack of soundings. Excluding North America soundings (which we decided not to use because of large day-to-day temperature variations), the only soundings available were those from Antofagasta, Chile (SCFA), a few CFH soundings launched from San Jose, Costa Rica (MROC), and a handful of soundings launched from the Japanese research ship Hakuho-Maru (HM).

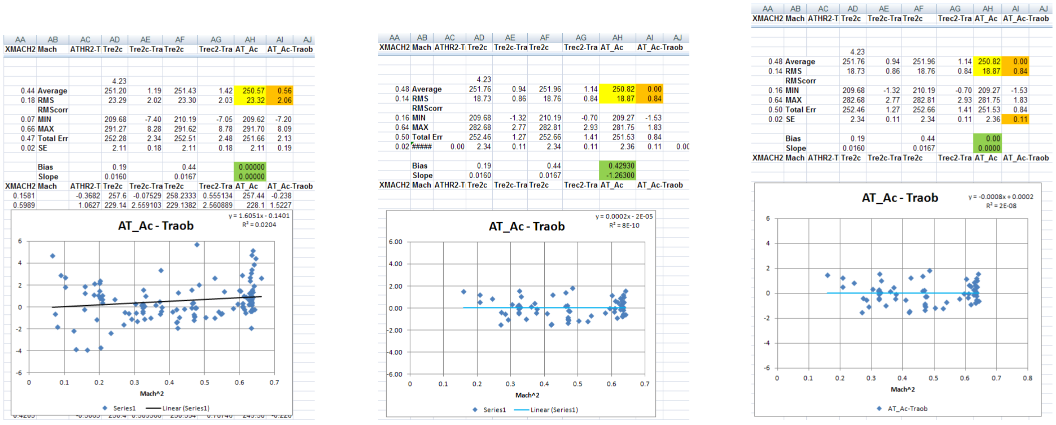
The SCFA soundings were normal WMO soundings. Their only short-coming was that they were launched only at 12 UT, not when the GV was flying. As a result they tended to have an isothermal layer from the surface up to 2-4 km. The MTP measurements always showed much warmer temperatures in this region, so the retrieval coefficients that we used down low were not optimal.

As for the CFH soundings launched from MROC and HM, they were riddled with challenges that had to be overcome. They had non-standard formats, up to 14,000 levels, both ascent and descent measurements and so on. More time was spent dealing with these challenges than all the remaining data processing. The biggest challenge involved the fact that there was generally only one sounding for each comparison. Normally we look at the 'before' and 'after' soundings to make sure that there is no significant temperature variability which could degrade the quality of the comparison. Since this wasn't an option, the analysis code had to be modified to allow single RAOB comparisons – this was a tedious process! (Generally, the CFH soundings were launched during takeoff or landing at MROC, or at the time of a dip near HM, so that the lack of a second sounding for temporal interpolation was not a serious problem.)

Based on our experience from prior GV field campaign temperature calibrations, where the avionics temperature produced the best results, we decided to proceed with the temperature calibration for TORERO using the avionics temperature. This would save time waiting for the research temperatures to be calibrated. It turns out that there were 123 potential comparisons possible; however, we decided not to use the North American sounding on the two ferry flights between RMMA and San Jose, Costa Rica, because they wouldn't be representative of the more tropical conditions encountered during most of the campaign, and because there was large temperature variability and most of the comparisons were rather distant. This left 65 comparisons on which to do the temperature calibration. For the temperature calibration we used the procedure that calibrates the *in situ* temperature as a function of Mach Number squared. Using this procedure we found that the avionics temperature ($AT\_A$), when forced to agree with the 65 radiosonde comparisons near the GV flight track, had the following corrected ($AT\_Ac$) value:

$$AT\_Ac = AT\_A - 1.26300 * Mach^2 + 0.042930 \tag{1}$$

The Mach Number corrections for these corrected temperature measurements are important; it varies from -0.23 K to +0.38 K depending on the Mach Number, or a range of 0.61 K.



(a) (b) (c)

Figure 19: (a) One hundred and twenty-three radiosonde comparisons WITHOUT a Mach Number correction; (b) Sixty-five WITH a Mach Number correction. The green cells show the bias and slope of the Mach Number correction; and (c) Sixty-five with a Mach Number correction correction applied in the analysis code to verify the correction. Note that the bias and slope of the Mach Number correction is zero (green cells).

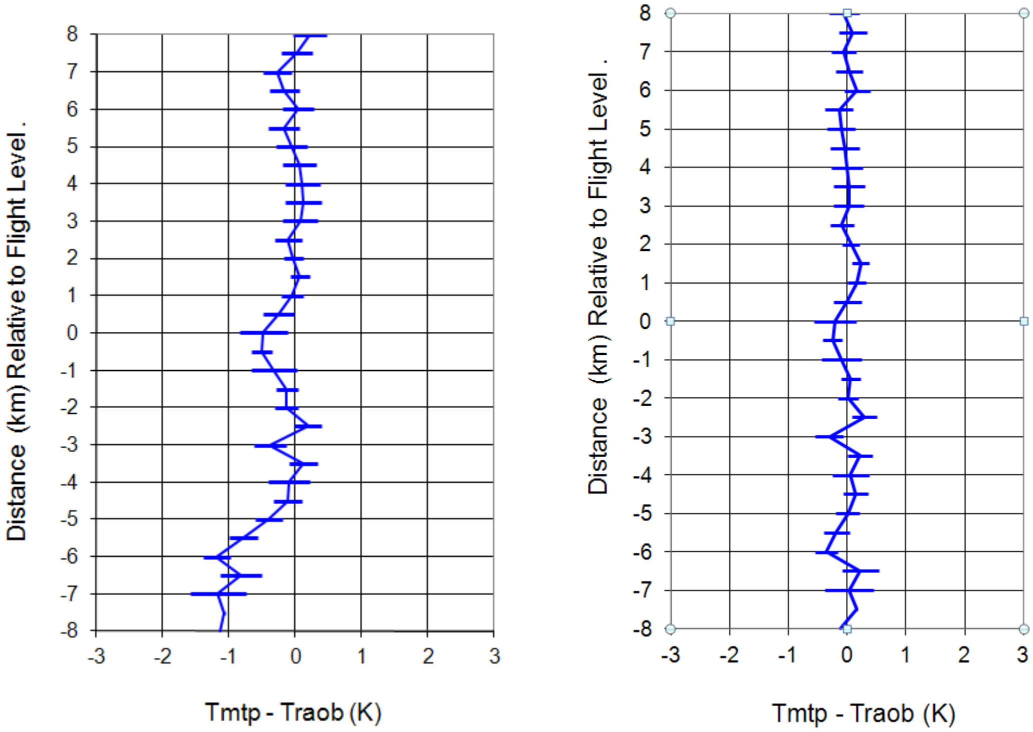
$$G = \frac{Counts(Horizon) - Counts(Target)}{ATHR2c - T_{target}} \qquad (2)$$

where Counts (Horizon) and Counts (Target) are just the output of the MTP when looking at the horizon (i.e., an *in situ* measurement in front of the GV) and the reference target. (The gain calculation is actually not this simple because of emissivity and reflectivity issues, but we'll spare you the details!) With the gains in hand, we could now do retrievals. After the first pass through all the flights, we calculate what we call a Window Correction Table (WCT). These are small temperature corrections that are applied to the measured brightness temperatures to correct for scan mirror side lobes. By design the WCT is always 0.0 K when the scan mirror elevation angle is zero, so this does not affect the flight level temperature calibration. Another retrieval pass is made through all the flights with the WCT applied. At this point we assess the accuracy of the MTP retrievals at all retrieval altitudes, not just flight level. This is done in Figure 20. In Figure 20a we show the MTP accuracy with respect to flight level for the 125 radiosonde comparisons. It is obvious that there is a small cold bias (~1 K) more than 5 km below flight level. We believe that this is due to the ocean temperature being colder than the air temperature just above it. We have an algorithm that can deal with this issue, but instead we took a simpler approach (to save time), which we call the RAF-correction (REF-file After Fix, or RAF). Since the accuracy assessment is telling us that the MTP retrieved temperatures are too cold below the aircraft, we simply do a sixth-order polynomial fit to determine the correction that gives the smallest over-all bias with respect to radiosondes. This is shown in Figure 20b. Note that this does create a very small bias at flight level; however, our goal is to provide the best retrieved temperatures at all retrieval levels, not just flight level.

## 2.3 Sanity Check

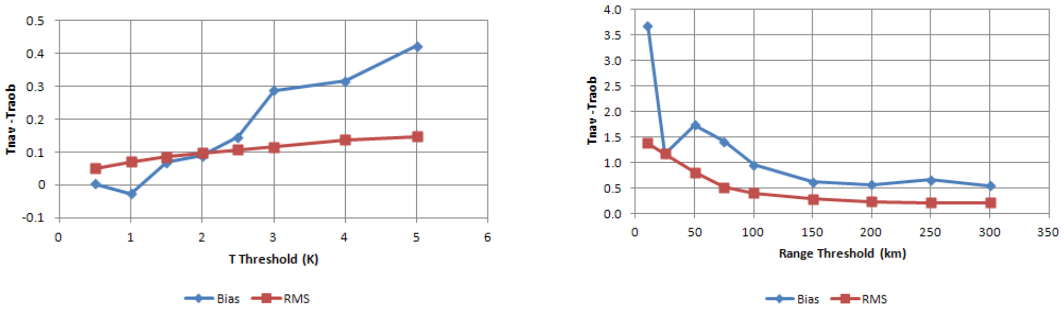
When we calibrate the *in situ* temperature, there are a number of sanity checks that we perform. In part these have to do with deciding which, if any, of the possible RAOB comparisons should be excluded. The only ground rule on these checks is that they be completely objective. Two obvious checks involve looking at how the bias and rms of the nav temperature minus the RAOB temperature (Tnav - Troab) vary as a function of a temperature threshold or as a function of the range or distance from the RAOB launch site.

Figure 21a shows a temperature threshold comparison. Basically, the Tnav - Traob values for each comparison are checked against a threshold temperature. For example, if the threshold temperature is 3 K then all differences whose absolute value exceeds 3 K are removed and the bias and rms of the remaining comparisons are calculated. Figure 21a shows the results. Often when this is done as the



(a) (b)

Figure 20: Assessment of MTP performance relative to radiosondes (a) BEFORE RAF correction; and (b) AFTER RAF correction.



(a) (b)

Figure 21: (a) A temperature threshold comparison; and (b) a range threshold comparison.

threshold gets smaller and smaller the rms will tend to go up because of the decreasing statistics. For TORERO however because we had so many accurate comparisons, the rms continued to monotonically decrease, and in fact from this plot we can safely say that there is no statistically significant bias below 2 K, since the lbrown curve representing the rms lies above the blue curve representing the bias.

Figure 21b shows a range threshold comparison. In this case comparisons exceeding a specified distance from the RAOB launch site are removed and the bias and rms of the remaining comparisons is calculated. During TORERO there were few comparisons at close range, which is to be expected when flying over mainly oceanic regions. So in this comparison, the rms begins to increase at distances closer than 150 km. There appears to be a 0.5 K warm bias in Tnav - Trms since the rms is always $< 0.3$ K. We're not sure what to make of this result, other than that at the shorter distances ($< 150$ km) where we would expect the performance to improve there are not enough comparisons to provide good statistics.