A Summary of MTP Results for HIPPO-2

Julie Haggerty[1] and MJ Mahoney[2]

[1]NSF NCAR
[2]JPL

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Introduction

We summarize in this document, the results of the analysis of the Microwave Temperature Profiler (MTP) data obtained on the NSF/NCAR GV (NGV) during the HIPPO-2 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 HIPPO-2 MTP dataset so that users can obtain a summary of data quality and interesting features associated with each flight. We provide information on how the temperature was calibrated for the HIPPO-2 campaign.

1 Results

Comments on the HIPPO-2 MTP Final Data

Color-coded temperature curtain (CTC) plots are available for each of the HIPPO-2 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. These comments are important because the rapid ascents and descents of the GV during the HIPPO campaigns degrade the quality of the MTP retrievals. On the other hand, this profiling – as will be discussed below – allowed very accurate temperature calibration.

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 an ~20 second MTP scan, this is not the case. 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 behaviour 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 is can be used or not. All the MTP final data have been edited to include retrievals with the MRI < 1. 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.

For most of the flights the CTC plots (which in fact are plotted using the archived data) are 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 TF01

Local test flight from RMMA

The two short test flights out of RMMA have a lot of radio frequency interference in the MTP data. MP-files will not be provided unless someone really wants them (Figure 1).

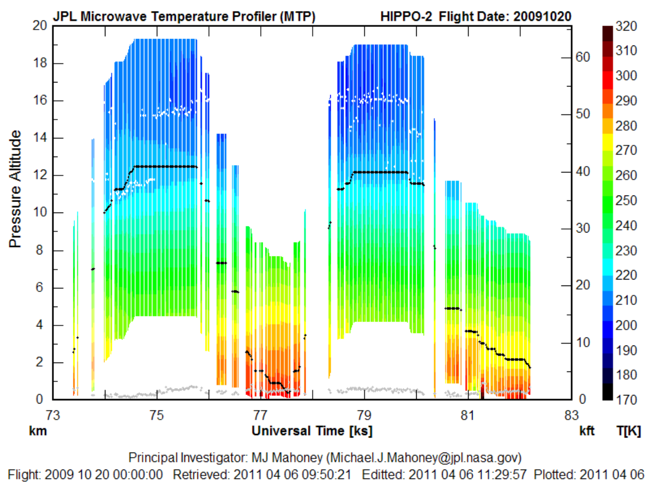


Figure 1: CTC Plot from Test Flight 1 on October 20, 2009

1.2 TF02

Local test flight from RMMA

The two short test flights out of RMMA have a lot of radio frequency interference in the MTP data. MP-files will not be provided unless someone really wants them (Figure 2).

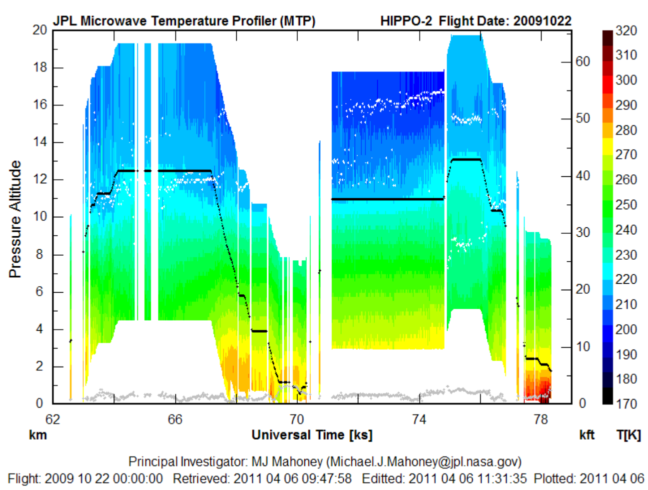


Figure 2: CTC Plot from Test Flight 2 on October 22, 2009

1.3 RF01

Transit flight from RMMA to Anchorage, Alaska

The data up to ~65 ks UT cannot be trusted because the a priori dataset did not match the measurements. Beyond this period, the data look good (Figure 3).

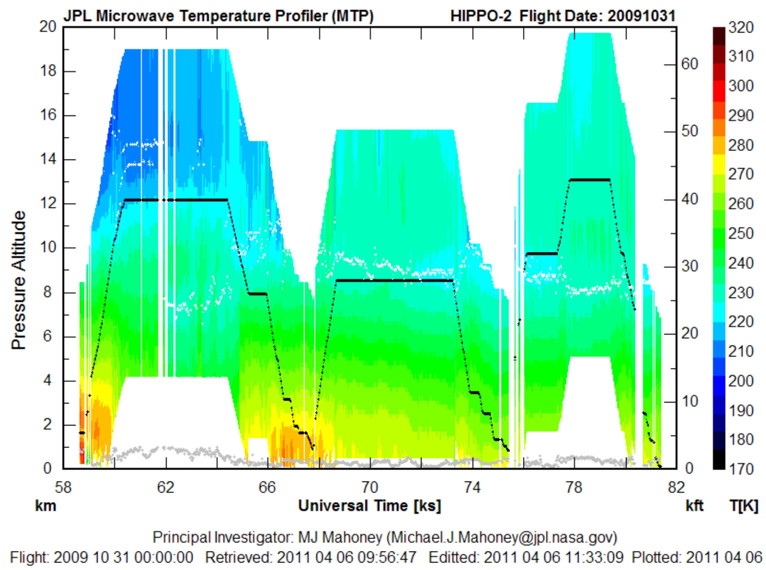


Figure 3: CTC Plot from Research Flight 1 on October 31, 2009

1.4 RF02

Anchorage, Alaska, to the North Pole and back

There was radio frequency interference on and off between 74 and 84 ks. Otherwise the retrievals look good (Figure 4).

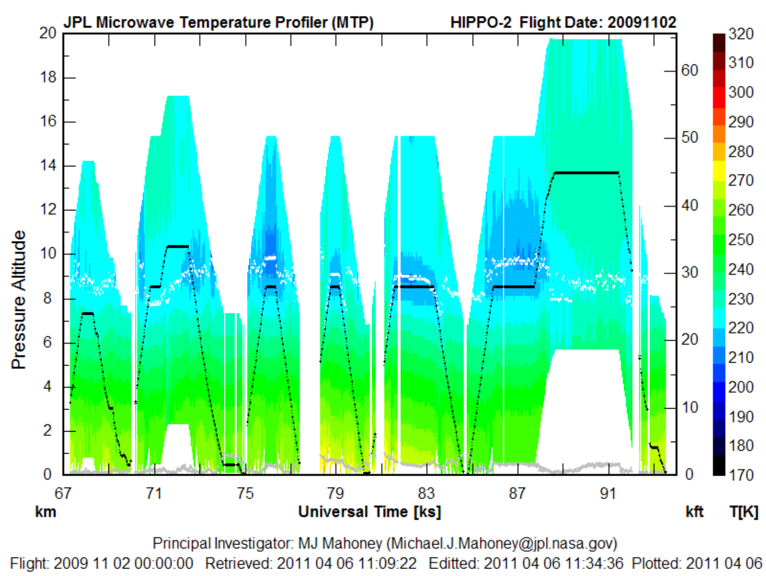


Figure 4: CTC Plot from Research Flight 2 on November 2, 2009

1.5 RF03

Anchorage, Alaska to Kona, Hawaii

There was some interference at 83, 95, and 88 ks, but otherwise the data look good (Figure 5).

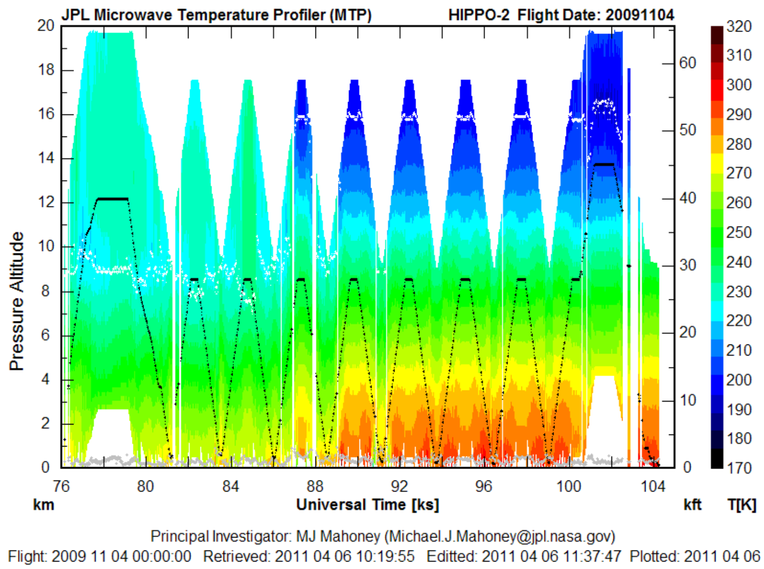


Figure 5: CTC Plot from Research Flight 3 on November 4, 2009

1.6 RF04

Kona, Hawaii to Raratonga, Cook Islands

This flight looks very good. The retrieval range was increased to ±10 km from flight level in order to show the tropopause (Figure 6).

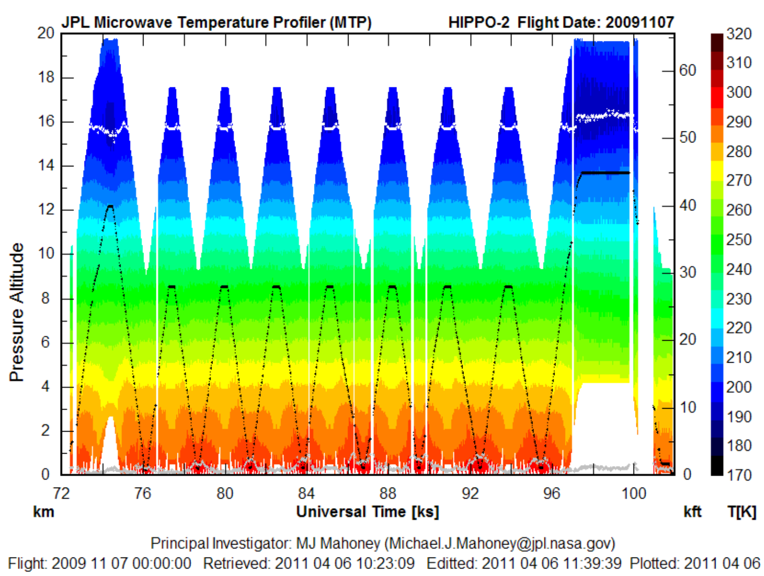


Figure 6: CTC Plot from Research Flight 4 on November 7, 2009

1.7 RF05

Raratonga, Cook Islands to Christchurch, New Zealand

These data look very good (Figure 7).

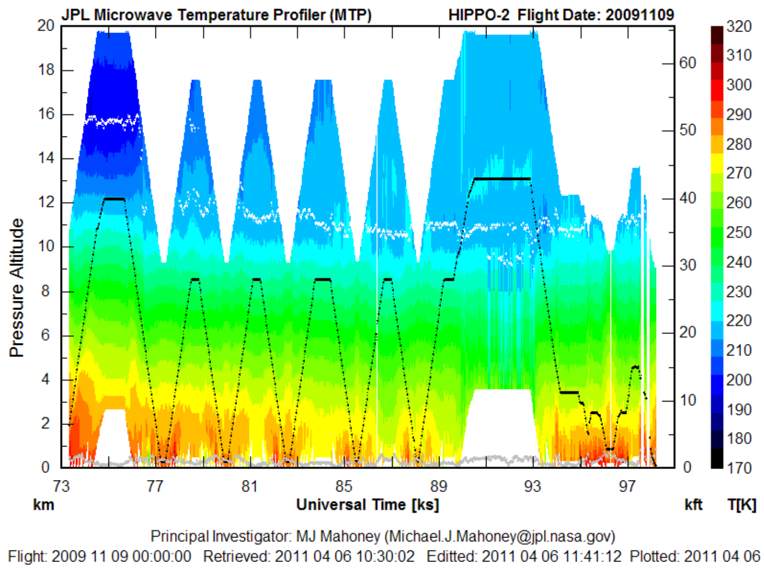


Figure 7: CTC Plot from Research Flight 5 on November 9, 2009

1.8 RF06

Christchurch, New Zealand to the South Pole and back

There was some bad interference from ~91-94 ks when the GV was low; otherwise, the data look good (Figure 8).

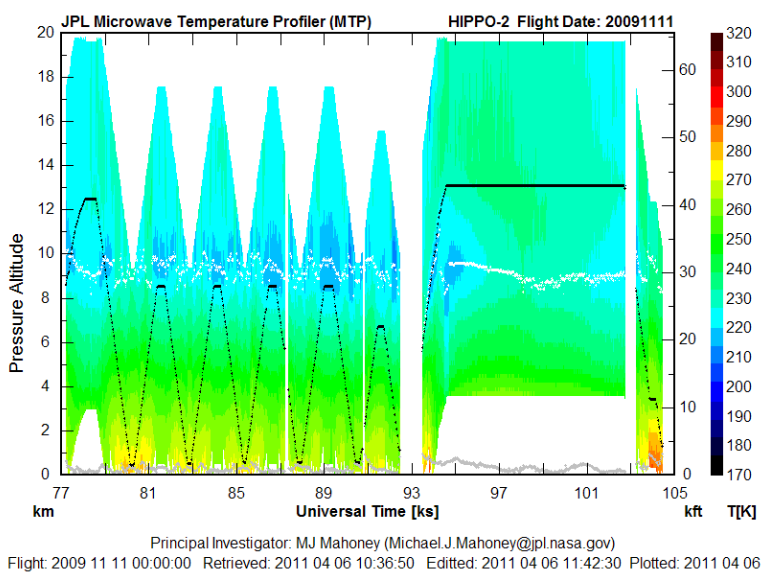


Figure 8: CTC Plot from Research Flight 6 on November 11, 2009

1.9 RF07

Christchurch, New Zealand to Honiara, Solomon Islands

The a priori data did not match the measurements very well at ~77 ks. The noisy tropopause at ~88 ks is not real. It was caused by the rapid descent, but we wanted to provide data ±10 km from flight level so that the high tropical tropopause after 94 ks could be seen (Figure 9).

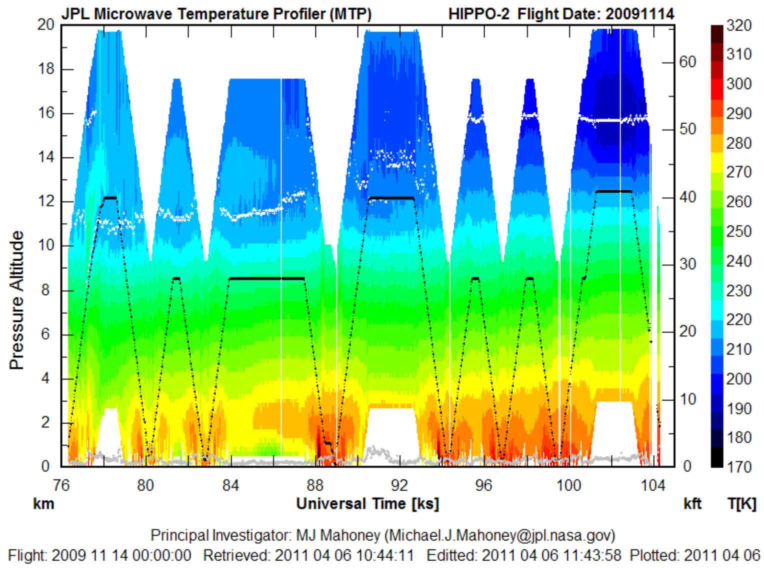


Figure 9: CTC Plot from Research Flight 7 on November 14, 2009

1.10 RF08

Honiara, Solomon Islands to Kona, Hawaii

We will use this flight as a very successful performance example! The retrievals are excellent. The retrieval range was increased to ±10 km from flight level in order to show the tropopause (Figure 10).

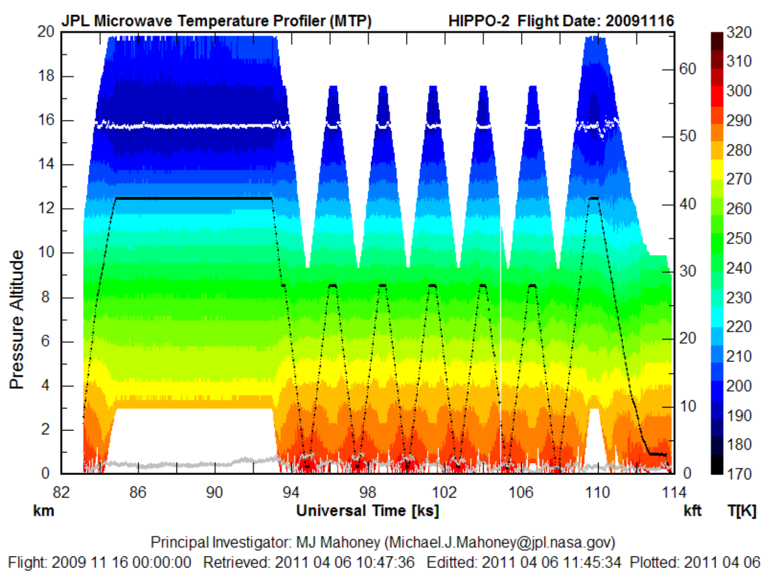


Figure 10: CTC Plot from Research Flight 8 on November 16, 2009

1.11 RF09

Kona, Hawaii to Anchorage, Alaska

The retrievals are a little noisy, but otherwise very good. We believe that the tropopause drop near the end of the flight (~96 ks) approaching Anchorage is real. The GV likely entered the polar vortex at that time(Figure 11).

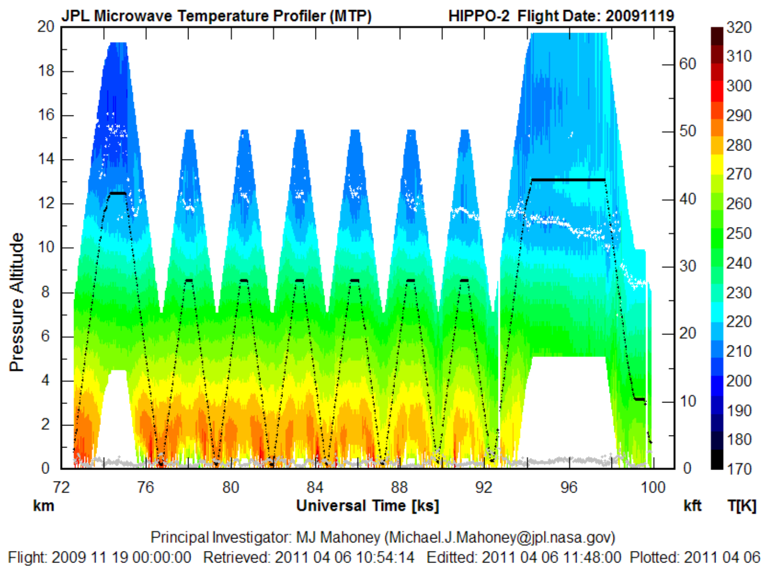


Figure 11: CTC Plot from Research Flight 9 on November 19, 2009

1.12 RF10

Anchorage, Alaska to North Pole and back

The a priori data did not match the measurements as well as might be desired. Because of this the tropopause height appears a little noisy (Figure 12).

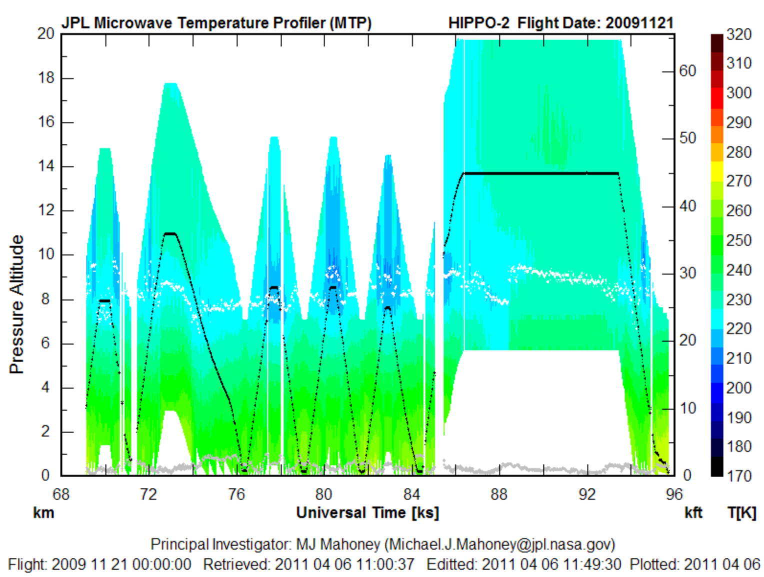


Figure 12: CTC Plot from Research Flight 10 on November 21, 2009

1.13 RF11

Transit flight from Anchorage, Alaska to RMMA

The a priori data did not match the measurements very well at ~80 ks. Otherwise the retrievals look fine (Figure 13).

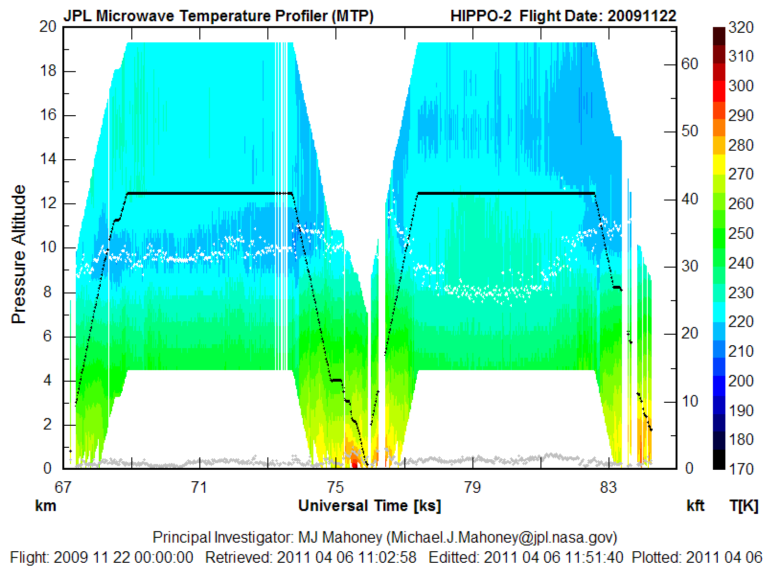


Figure 13: CTC Plot from Research Flight 11 on November 22, 2009

2 HIPPO-2 Temperature Calibration

2.1 Background

For nearly two decades the MTP team has been refining techniques for calibrating *in situ* temperature measurements made aboard research aircraft using 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. It was realized that if the flight level temperature was calibrated independently of the MTP data that 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 **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. There are other documents that describe this procedure for START-08, HIPPO-1, and HIPPO-3. In fact, much of this discussion is a repeat of what is one the HIPPO-3 document since the HIPPO-2 data was processed after the HIPPO-3 data.

Before discussing the calibration procedure for the HIPPO-2 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 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 would 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). Instead of using the great-circle time of closest approach to make the comparison, we decided to do comparisons every 2 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 HIPPO-2 Specifics

For HIPPO-2 there were five in situ temperature measurements that were available for radiosondes comparisons: **AT_A**, **ATHL1**, **ATHL2**, **ATHR1**, and **ATHR2**. (The fast response temperature **ATFR** was not used – apparently because it ices up.) When we analyzed the data for HIPPO-1, we initially attempted to do a correction to the *in situ* temperatures as a function of pressure altitude. However, since the correction from total temperature (Tt) to static temperature (Ts) involves Mach Number squared (see this web page for more information, this equation ignores the recovery factor):

$$\frac{T_r}{T_s} = 1 + r\frac{\gamma - 1}{2}M^2 \tag{1}$$

and the MTP data processing software did not use Mach Number, we needed to create a proxy for Mach Number as a function of pressure altitude Zp. We did this for a segment of a HIPPO-1 flight on 20090109, and obtained:

$$M^2(Zp) = 0.02089 + 0.06555Zp - 0.00122Zp^2 \tag{2}$$

This approach has some inherent error however, since there is not a one-to-one correspondence between pressure altitude and Mach Number. Therefore, when dealing with the HIPPO-2 (and the previously completed HIPPO-3) temperature calibrations, we decided to update the data analysis software and spreadsheets to use Mach Number squared (M^2). Using Tx to represent one of the five in situ temperature measurements available for HIPPO-2, we plotted **Tx-Traob** versus M^2, and found for the corrected temperatures (sub-script 'c'):

$$AT\_Ac = AT\_A * (1 - 0.0020 * M^2) - 0.42$$

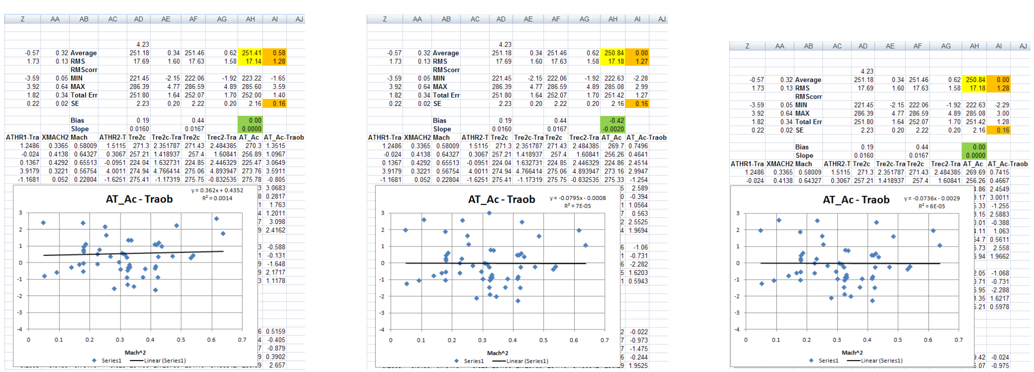
$$ATHL1c = ATHL1 * (1 + 0.0129 * M^2) - 0.01$$

$$ATHL2c = ATHL2 * (1 + 0.0122 * M^2) - 0.61$$

$$ATHR1c = ATHR1 * (1 + 0.0229 * M^2) - 1.17$$

$$ATHR2c = ATHR2 * (1 + 0.0168 * M^2) - 0.74$$

The Mach Number corrections for these corrected temperature measurements are important. For example the maximum value of Mach Number squared when we made radiosonde comparisons was 0.64. If we assume a nominal temperature of 200 K at this Mach Number then the corrections in these five equations are -0.68 K, 1.64 K, 0.95 K, 1.76 K, and 1.41 K, respectively. These are large temperature corrections, having a range of 2.44 K! Notice that Mach Number correction (the coefficient of M^2) is 6 to 11 times as large for the four research temperatures, as it is for the avionics temperature (AT_A). Also, in this example AT_A had the smallest correction (-0.68 K) for $M^2 = 0.64$. For these and other reasons (smallest scatter, being used by the project), we adopted the corrected AT_A (that is, AT_Ac) as the *in situ* temperature to be used for HIPPO-2 to calibrate the MTP gain.



(a) (b) (c)

Figure 14: Sixty-four radiosonde comparison (a) WITHOUT a Mach Number correction; (b) WITH a Mach Number correction. The green cells show the bias and slope of the Mach Number correction; and (c) 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).

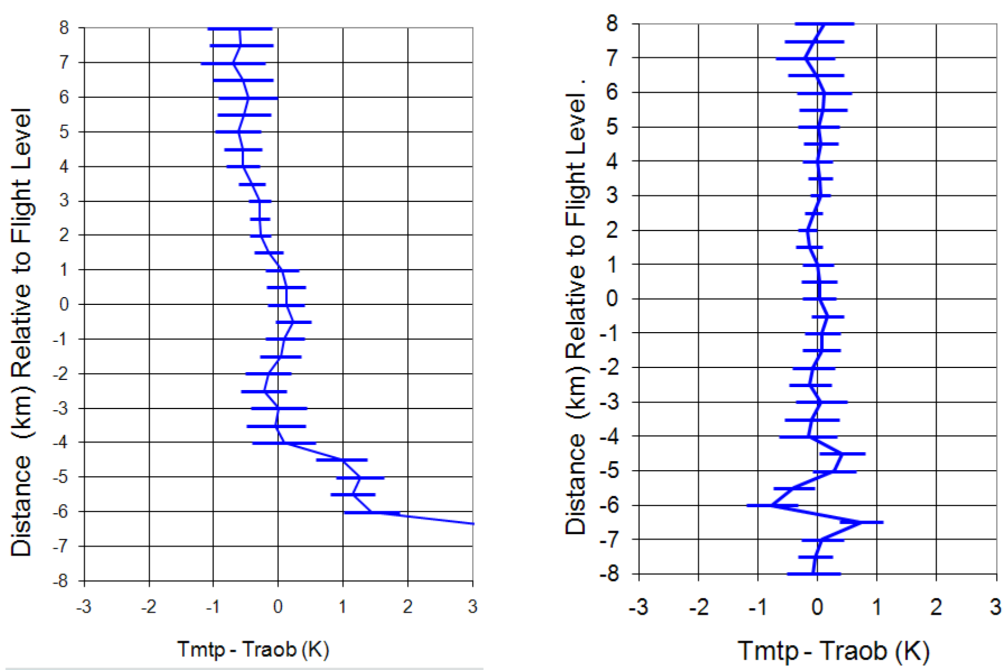
Because we did radiosonde comparisons every 2 km from 2 km on up whenever the GV made a descent and ascent, we ended up with 109 potential comparisons within a range of 160 km of the aircraft. After these were edited for the criteria discussed above, including non-redundancy, the total number of comparisons was reduced 64. Figure 14a shows these 64 comparisons without a Mach Number correction, Figure 14b shows the same comparisons with a bias correction of -0.42 K and a slope correction of -0.0020, and Figure 14c just verifies that when the corrections were applied in the data analysis software that the bias and slope corrections go to zero. Note the 'slope correction' is really pressure altitude correction, but it is more closely tied to Mach Number Squared than it is to pressure altitude.

With the corrected avionics temperature (AT_Ac) in hand, we could calculate the MTP instrument gains for each observing frequency in Counts/Kelvin as:

$$G = [Counts(Horizon) - Counts(Target)]/[AT\_Ac - T_{target}] \quad (3)$$

where Counts (Horizon) and Counts (Target) are just the output of 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, 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 now 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 15. In Figure 15a we show the MTP accuracy with respect to flight level for the 64 radiosonde comparisons. It is obvious that the retrieved MTP temperatures below the aircraft have a warm bias relative to radiosondes. This happens on the HIPPO flights because when the GV descends toward the ocean, the MTP 'sees' emission from the ocean which is warmer than the air just above it. We have algorithms that can deal with this issue, but instead we took a simpler approach (to save time), which we call the RAF-correction. This has absolutely nothing to do with an NCAR research facility, but rather stands for REF-file After Fix (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 15b. 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.



(a) (b)

Figure 15: MTP Accuracy with respect to flight level: (a) assessment of MTP performance relative to radiosondes BEFORE RAF correction; (b) assessment of MTP performance relative to radiosondes AFTER RAF correction.