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# **Analysis of the WindSat Receiver Frequency Passbands**

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| <b>14. ABSTRACT</b><br><br>The WindSat instrument is the primary payload for the Coriolis mission which was launched on 6 January 2003. WindSat is a 22-channel conical-scanning radiometer which measures the vertical and horizontal polarizations at nominal center frequencies of 6.8 and 23.8 GHz and six polarizations at nominal center frequencies of 10.7, 18.7, and 37 GHz. The prelaunch WindSat receiver frequency passband measurements are presented and modeled with a functional fit. Radiative transfer simulations are presented which model the differences between the measured brightness temperatures for ocean scenes and the simulated brightness temperatures for the nominal design receiver frequency passbands. Significant differences are shown for the channels with 18.7 and 23.8 GHz nominal center frequencies. These differences are shown to be a function of the precipitable water vapor in the measured scene.     |                                                 |                                                  |                                                                    |                                                                             |                                                                    |
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# ANALYSIS OF THE WINDSAT RECEIVER FREQUENCY PASSBANDS

## 1. INTRODUCTION

The WindSat instrument is the primary payload for the Coriolis mission which was launched on 6 January 2003. WindSat is a 22-channel conical-scanning radiometer which measures the vertical and horizontal polarizations at nominal center frequencies of 6.8 and 23.8 GHz and six polarizations (vertical (V), horizontal (H),  $+45^\circ$  linear (P),  $-45^\circ$  linear (M), left circular (L) and right circular (R)) at nominal center frequencies of 10.7, 18.7 and 37 GHz.

The WindSat receiver subsystem is divided into three units: the front-end receiver (FER), the receiver electronics unit (REU) and the detector electronics unit (DEU). A more detailed description of the WindSat instrument and the receiver subsystem can be found in Gaiser, et al. [1]. The receiver frequency passband response is primarily determined by the band pass filter in the REU. The characteristics of the frequency passband responses can have a significant effect on the measured brightness temperatures ( $T_b$ 's) [2].

## 2. MEASURED RECEIVER PASSBANDS

The WindSat receiver frequency passband responses were measured pre-launch at three different temperatures: 0, 25 and  $40^\circ\text{C}$ . The only passband measurements currently available for channels with a nominal center frequency of 10.7 GHz are those taken at  $25^\circ\text{C}$ . Passband measurements are available at all three temperatures for all other channels.

The passband measurements provide receiver frequency passband responses for each WindSat receiver at 401 evenly-spaced frequencies over the passband. The measurement frequencies were consistent for all channels with the same nominal center frequency. Figure 1 shows the receiver passband responses for all five WindSat vertically polarized channels. The range of frequencies over which the receiver passband responses were measured correspond to the minimum and maximum values shown on the frequency axes of the plots. Figure 1 also shows fits to the measured passband response of the form [2]

$$H_{\text{fit}} = \frac{A(B/2)^\alpha}{|v - v_0|^\alpha + (B/2)^\alpha \left[ 1 + a \frac{(v - v_0)}{(10^9 \text{Hz})} \right]} \quad (1)$$

where the fit parameters are center frequency,  $v_0$ , the bandwidth,  $B$ ,  $\alpha$ , and  $a$ . The sharpness of the edges of the passband fit is determined by  $\alpha$ . The factor  $a$  models asymmetry of the passband response about  $v_0$ . The passband responses were scaled so that  $A = 1$ . The fits were derived by using a Nelder-Mead algorithm [3, 4] to solve for the Equation (1) parameters which minimize

$$\sum_i (H_{v,i} - H_{\text{fit},i})^2. \quad (2)$$

where  $H_{v,i}$  is the measured passband response at frequency  $i$  and  $H_{\text{fit},i}$  is the value of the fit at that frequency. Table 1 gives the fit parameters for all 22 WindSat receiver passbands. Section 3 describes a method for modeling the  $T_b$ 's integrated over the receiver frequency passband for a set of atmospheric profiles. The  $v_0$  column in Table 1 gives the values which result from minimization of Equation (2) with small adjustments to remove ( $<0.35$  K) biases in the modeled  $T_b$ 's when using the fits for the passbands. These adjustments to  $v_0$  were calculated using a one-dimensional bracketing optimization to reduce the biases to less than 0.01 K. The receiver passband response fits produced using the parameters given in Table 1 are shown in Figure 2 for each WindSat frequency band.

Table 1: Optimized fit parameters for the WindSat receiver passbands using the functional form given in Equation (1).

| Channel | $T_{\text{REU}}$ ( $^{\circ}\text{C}$ ) | $v_0$ (GHz) | $B$ (MHz) | $\alpha$ | $a$     |
|---------|-----------------------------------------|-------------|-----------|----------|---------|
| 6.8 V   | 0                                       | 6.804       | 125.7     | 14.359   | 0.3801  |
|         | 25                                      | 6.800       | 126.4     | 15.241   | 0.4492  |
|         | 40                                      | 6.798       | 126.5     | 15.406   | 0.4972  |
| 6.8 H   | 0                                       | 6.803       | 122.7     | 12.156   | 0.0920  |
|         | 25                                      | 6.801       | 122.4     | 11.666   | 0.0090  |
|         | 40                                      | 6.799       | 122.3     | 11.565   | -0.0207 |
| 10.7 V  | 25                                      | 10.700      | 308.4     | 11.104   | -0.7149 |
| 10.7 H  | 25                                      | 10.704      | 305.5     | 12.130   | -0.6207 |
| 10.7 P  | 25                                      | 10.703      | 305.1     | 12.304   | -0.4119 |
| 10.7 M  | 25                                      | 10.693      | 308.4     | 11.965   | -0.6213 |
| 10.7 L  | 25                                      | 10.700      | 320.3     | 14.542   | -0.4070 |
| 10.7 R  | 25                                      | 10.710      | 305.7     | 9.813    | -0.4244 |
| 18.7 V  | 0                                       | 18.732      | 705.4     | 7.555    | 0.2030  |
|         | 25                                      | 18.687      | 695.6     | 7.311    | 0.2614  |
|         | 40                                      | 18.691      | 729.0     | 9.243    | 0.1767  |
| 18.7 H  | 0                                       | 18.759      | 775.3     | 10.492   | -0.0998 |
|         | 25                                      | 18.742      | 766.3     | 9.706    | 0.0454  |
|         | 40                                      | 18.734      | 760.9     | 9.269    | 0.1184  |
| 18.7 P  | 0                                       | 18.728      | 758.3     | 12.664   | -0.2920 |
|         | 25                                      | 18.716      | 758.1     | 12.688   | -0.2857 |
|         | 40                                      | 18.712      | 755.7     | 12.597   | -0.3059 |
| 18.7 M  | 0                                       | 18.720      | 775.7     | 13.178   | 0.0020  |
|         | 25                                      | 18.707      | 777.7     | 13.344   | -0.0052 |
|         | 40                                      | 18.704      | 778.6     | 13.412   | 0.0100  |
| 18.7 L  | 0                                       | 18.725      | 738.8     | 9.870    | 0.3491  |
|         | 25                                      | 18.712      | 731.4     | 9.809    | 0.3930  |
|         | 40                                      | 18.708      | 729.8     | 9.745    | 0.4035  |
| 18.7 R  | 0                                       | 18.721      | 774.1     | 10.634   | 0.1048  |
|         | 25                                      | 18.703      | 757.4     | 9.507    | 0.0409  |
|         | 40                                      | 18.695      | 747.9     | 8.968    | 0.0443  |

Table 1: (continued)

| Channel | $T_{\text{REU}} (^{\circ}\text{C})$ | $\nu_0(\text{GHz})$ | $B (\text{MHz})$ | $\alpha$ | $a$     |
|---------|-------------------------------------|---------------------|------------------|----------|---------|
| 23.8 V  | 0                                   | 23.802              | 499.0            | 7.646    | -0.3708 |
|         | 25                                  | 23.787              | 493.9            | 7.943    | -0.1666 |
|         | 40                                  | 23.777              | 490.2            | 8.249    | -0.0772 |
| 23.8 H  | 0                                   | 23.807              | 510.5            | 5.828    | -0.7423 |
|         | 25                                  | 23.793              | 503.8            | 5.731    | -0.6026 |
|         | 40                                  | 23.781              | 503.5            | 5.725    | -0.5079 |
| 37 V    | 0                                   | 37.025              | 1991.7           | 12.431   | 0.0585  |
|         | 25                                  | 37.006              | 1955.2           | 10.984   | -0.0810 |
|         | 40                                  | 36.999              | 1946.9           | 10.372   | -0.0688 |
| 37 H    | 0                                   | 36.968              | 1996.6           | 11.248   | -0.2271 |
|         | 25                                  | 36.951              | 1944.8           | 7.561    | -0.3128 |
|         | 40                                  | 36.942              | 1970.4           | 8.306    | -0.2279 |
| 37 P    | 0                                   | 37.023              | 1801.3           | 7.213    | 0.0207  |
|         | 25                                  | 36.999              | 1734.1           | 6.268    | -0.0564 |
|         | 40                                  | 36.989              | 1752.3           | 6.337    | -0.0812 |
| 37 M    | 0                                   | 37.028              | 2008.9           | 18.472   | -0.1300 |
|         | 25                                  | 37.007              | 2006.6           | 17.059   | -0.1352 |
|         | 40                                  | 37.007              | 1997.9           | 15.277   | -0.0888 |
| 37 L    | 0                                   | 37.006              | 1842.9           | 8.819    | -0.2001 |
|         | 25                                  | 36.982              | 1797.0           | 7.304    | -0.2805 |
|         | 40                                  | 36.973              | 1751.9           | 6.097    | -0.3281 |
| 37 R    | 0                                   | 36.980              | 1956.2           | 10.761   | -0.0537 |
|         | 25                                  | 36.961              | 1910.2           | 8.300    | -0.1213 |
|         | 40                                  | 36.945              | 1854.9           | 6.361    | -0.2148 |

### 3. MODELING RESULTS

The results presented here were obtained using the analysis method described in [2]. The  $T_b$  is calculated by integrating the product of the measured receiver response  $H_\nu$ , or an idealized receiver response, and the modeled monochromatic brightness temperature ( $T_{b,\nu}$ ) over the receiver passband.

$$T_b = \frac{\int_0^\infty d\nu T_{b,\nu} H_\nu}{\int_0^\infty d\nu H_\nu} \quad (3)$$

The radiative transfer model used to calculate  $T_{b,\nu}$  combines the monochromatic radiative transfer model MonoRTM [5] with the Fresnel reflectivities for a specular sea surface obtained using the permittivity model for sea water developed by Stogryn [6]. The  $T_b$  are modeled for the WindSat channels using a selected subset of atmospheric profiles assembled by the Satellite Application Facility for Numerical Weather Prediction (NWP SAF) [7]. The subset was chosen to provide a diverse set of temperature, water vapor and cloud liquid water profiles while excluding most precipitation. The atmospheric profile set and the radiative transfer model are described in more detail in [2].



Radiative transfer modeling of WindSat  $T_b$ 's previously assumed idealized receiver frequency passband responses. For example, the forward model used for the ocean surface vector wind retrievals described in [8] assumed monochromatic passbands at the nominal center frequencies. Figure 3 shows differences between  $T_b$ 's calculated using the measured passbands for 25 °C receiver temperature and  $T_b$ 's calculated assuming monochromatic receiver responses at the nominal center frequencies. Significant differences are shown for the 18.7, 23.8 and 37 GHz bands. Differences for the 6.8 GHz band (not shown) are negligible ( $< 0.005$  K). The differences in Figure 3 are plotted versus the precipitable water vapor (PWV) calculated for each atmospheric profile. The differences for the 18.7 and 23.8 GHz bands vary with PWV.

Modeled  $T_b$ 's for receiver passbands using the functional fits per Equation (1) and Table 1 agree with modeled  $T_b$ 's using the measured receiver passbands to better than 0.01 K for all profiles and all channels. However, the functional fits for the receiver responses are difficult to apply for fast radiative transfer calculations. It can also be difficult to understand the importance of the differences between the receiver responses for different channels and temperatures from the functional fits. An alternative is to use a monochromatic model with the frequency shifted to best match the  $T_b$ 's obtained using the measured passbands. The  $T_b$ 's obtained using optimized monochromatic models are accurate to within 0.1 K for the 23.8 GHz horizontal polarization and to within 0.04 K for all other channels. The optimized frequency for the monochromatic model for each channel is given in Table 2 corresponding to the receiver passband measurements at 0, 25 and 40 °C.

The measured receiver passband responses clearly change with temperature as shown by the results Table 1 and 2. Table 3 provides one measure of the importance of these differences. The results show that the differences due to changes in the receiver temperature can be significant, although small, for the 18.7 GHz, 23.8 GHz and, to a lesser extent, the 37 GHz channels. The differences due to temperature are insignificant for the 6.8 GHz channels. It is also likely that receiver temperature effects are not significant for the 10.7 GHz channels based on the results for the other frequency bands.

The WindSat REU on-orbit temperatures have stayed in the range of about 24–39 °C throughout the mission as shown in Figure 4. This justifies only considering the 25 and 40 °C receiver temperatures for Table 3. The lowest REU temperatures are for the 10.7 GHz V/H REU and the highest are for the 37 GHz P/M REU. The REU temperatures for the other channels are displayed in light gray to show that the shape of the temperature distribution is similar for all channels. REU temperature varies primarily with solar illumination of the instrument. The temperature variations exhibit both annual and orbital cycles as shown in Figures 5–6, respectively. The 6.8 GHz receivers were turned off over the range of days 1956 to 1977 shown in Figure 5 which reduced the heat generated by WindSat and lowered the REU temperatures during that time period. Orbital variation is smallest in late February and largest in late May. The variations for separate orbits on the same day show only small differences under normal WindSat operating conditions.

#### 4. CONCLUSIONS

The WindSat receiver frequency passbands differ significantly from the nominal design for the instrument. Most importantly there are differences in the passbands within the same frequency band that can impact the measured  $T_b$ 's particularly for the 18.7 GHz frequency band. These differences will impact measurement of the third and fourth Stokes parameters which rely on matching between the P/M and L/R polarization pairs. As shown in Figure 3 the impact on the  $T_b$ 's varies primarily with the water vapor in the measurement scene. Additionally, receiver temperature changes can also modify the measured  $T_b$ 's particularly for the H-polarization channels at 18.7 and 23.8 GHz.

Table 2 — Frequencies in GHz for monochromatic modeling of the WindSat channel set based on radiative transfer calculations using receiver frequency passband measurements at 0, 25 and 40 °C.

| Channel | 0 °C   | 25 °C  | 40 °C  |
|---------|--------|--------|--------|
| 6.8 V   | 6.804  | 6.801  | 6.799  |
| 6.8 H   | 6.804  | 6.801  | 6.799  |
| 10.7 V  | -      | 10.705 | -      |
| 10.7 H  | -      | 10.708 | -      |
| 10.7 P  | -      | 10.706 | -      |
| 10.7 M  | -      | 10.699 | -      |
| 10.7 L  | -      | 10.704 | -      |
| 10.7 R  | -      | 10.713 | -      |
| 18.7 V  | 18.734 | 18.688 | 18.694 |
| 18.7 H  | 18.774 | 18.751 | 18.740 |
| 18.7 P  | 18.749 | 18.737 | 18.734 |
| 18.7 M  | 18.730 | 18.717 | 18.714 |
| 18.7 L  | 18.722 | 18.707 | 18.703 |
| 18.7 R  | 18.727 | 18.712 | 18.704 |
| 23.8 V  | 23.809 | 23.790 | 23.779 |
| 23.8 H  | 23.820 | 23.803 | 23.790 |
| 37 V    | 37.018 | 37.037 | 37.027 |
| 37 H    | 37.054 | 37.056 | 37.028 |
| 37 P    | 37.031 | 37.024 | 37.020 |
| 37 M    | 37.082 | 37.062 | 37.048 |
| 37 L    | 37.065 | 37.057 | 37.055 |
| 37 R    | 37.011 | 37.010 | 37.017 |

The analysis and effects discussed in this report apply only to non-precipitation ocean scenes. The effects are less significant for other surface types (land, sea ice, snow) because atmospheric effects are less important for those scenes. Additionally, for sea ice and snow the water vapor is in the lower part of the global water vapor range which further limits the effect on the  $T_b$ 's.

Caution must be used when applying the modeling results presented here to analysis of on-orbit WindSat data. The results here are solely based on radiative transfer modeling using pre-launch receiver characteristics. It is not known how accurately the pre-launch characteristics match with the on-orbit receiver characteristics throughout the mission.

Table 3 — The maximum difference between the calculated  $T_b$ 's using the measured receiver passbands for receiver temperatures of 25 °C ( $T_{b,25}$ ) and 40 °C ( $T_{b,40}$ ).

| Channel | $\max( T_{b,40} - T_{b,25} )$ (K) |
|---------|-----------------------------------|
| 18.7 V  | 0.08                              |
| 18.7 H  | 0.27                              |
| 18.7 P  | 0.07                              |
| 18.7 M  | 0.06                              |
| 18.7 L  | 0.08                              |
| 18.7 R  | 0.15                              |
| 23.8 V  | 0.13                              |
| 23.8 H  | 0.29                              |
| 37 V    | 0.02                              |
| 37 H    | 0.10                              |
| 37 P    | 0.01                              |
| 37 M    | 0.04                              |
| 37 L    | 0.01                              |
| 37 R    | 0.02                              |

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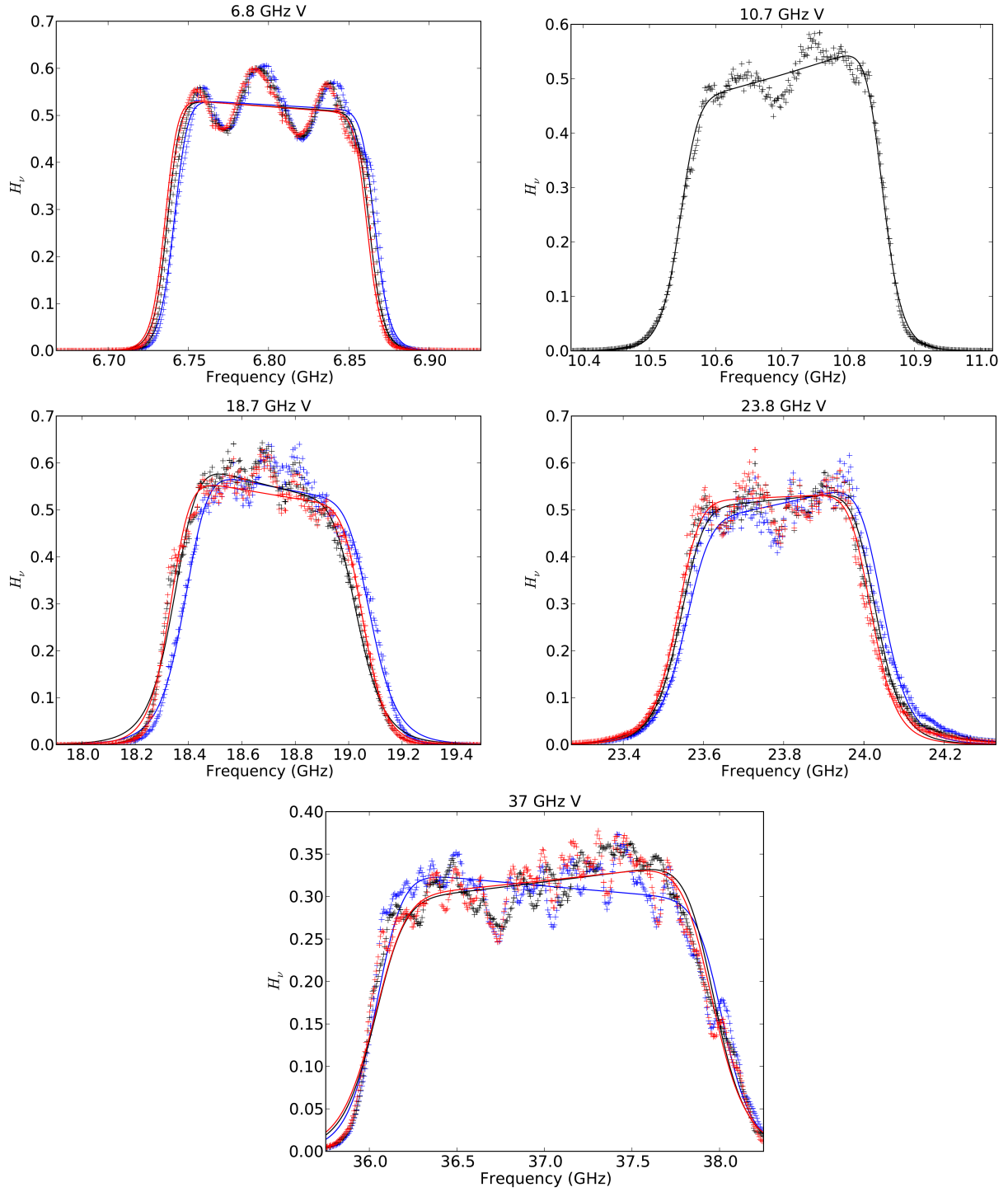


Fig. 1 — WindSat vertical polarization receiver passband responses. The measured responses are shown with the + signs and the solid lines are the functional fits in the form of Equation (1). The colors denote the receiver temperatures of 0°C (blue), 25°C (black) and 40°C (red).

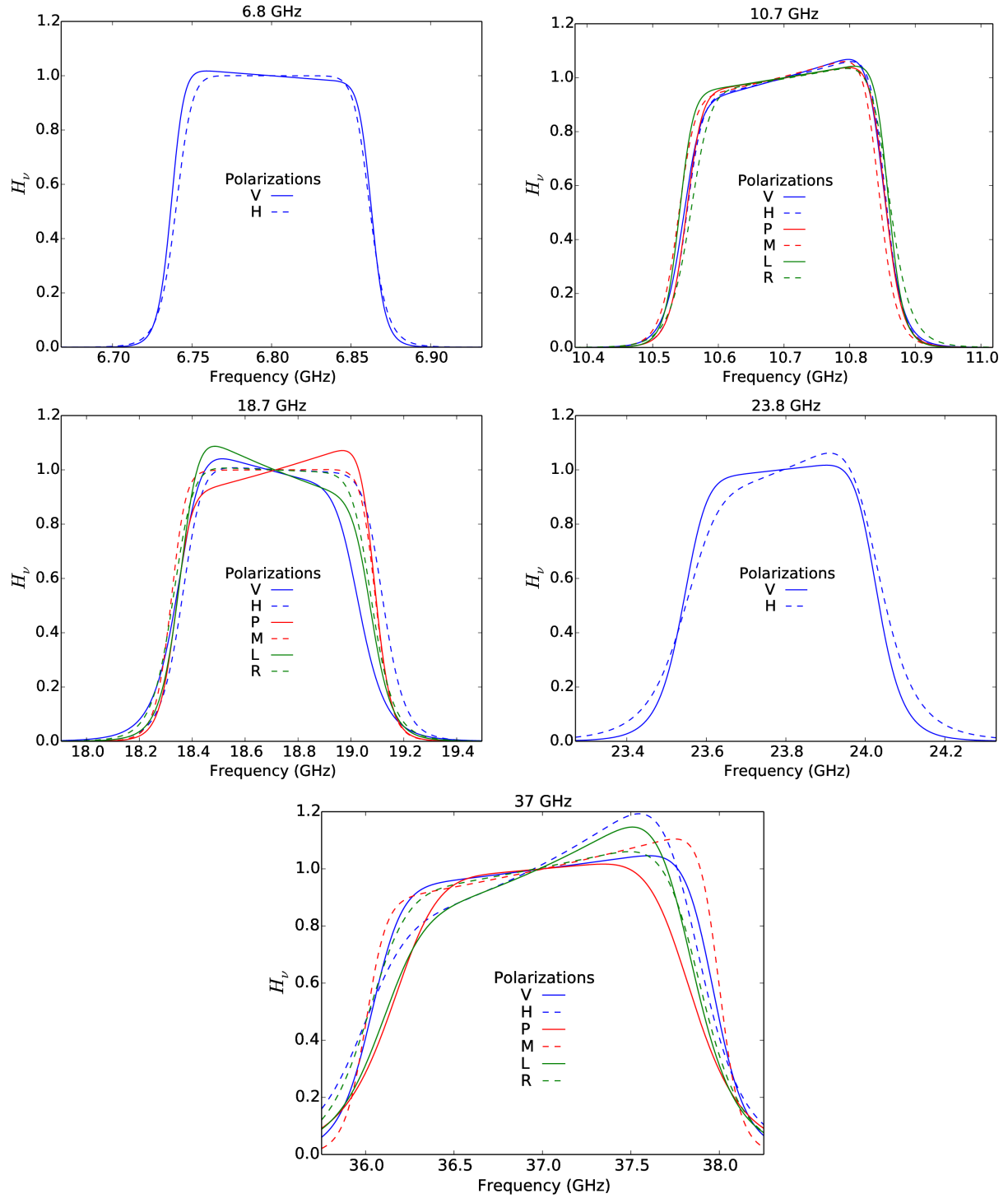


Fig. 2 — Optimized fits for the WindSat receiver passband responses measured at 25°C. All polarizations are shown for each WindSat frequency band.

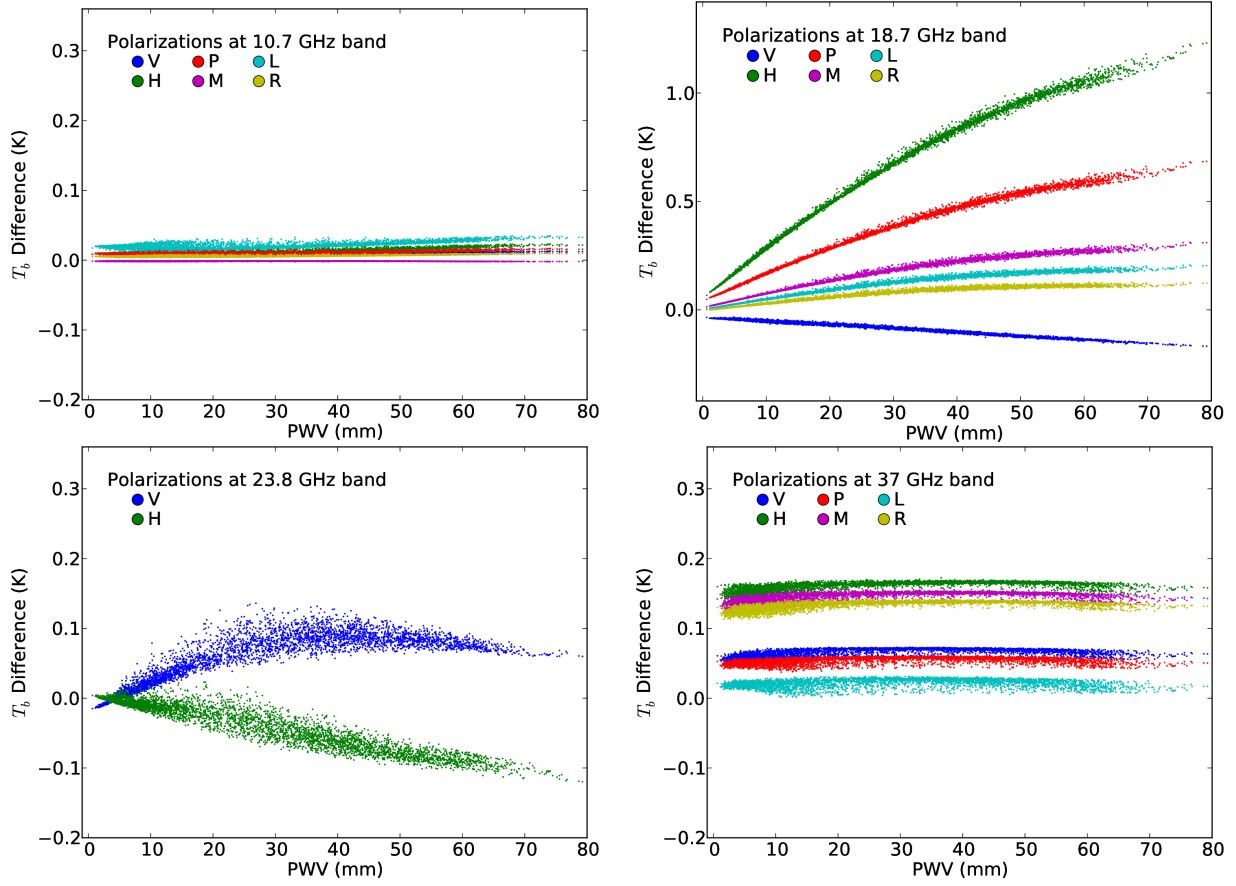


Fig. 3 — Modeled differences between the  $T_b$ 's integrated over the measured passbands and the  $T_b$ 's at the nominal center frequency for the respective bands ( $T_b - T_{b,mono}$ ) versus precipitable water vapor (PWV).

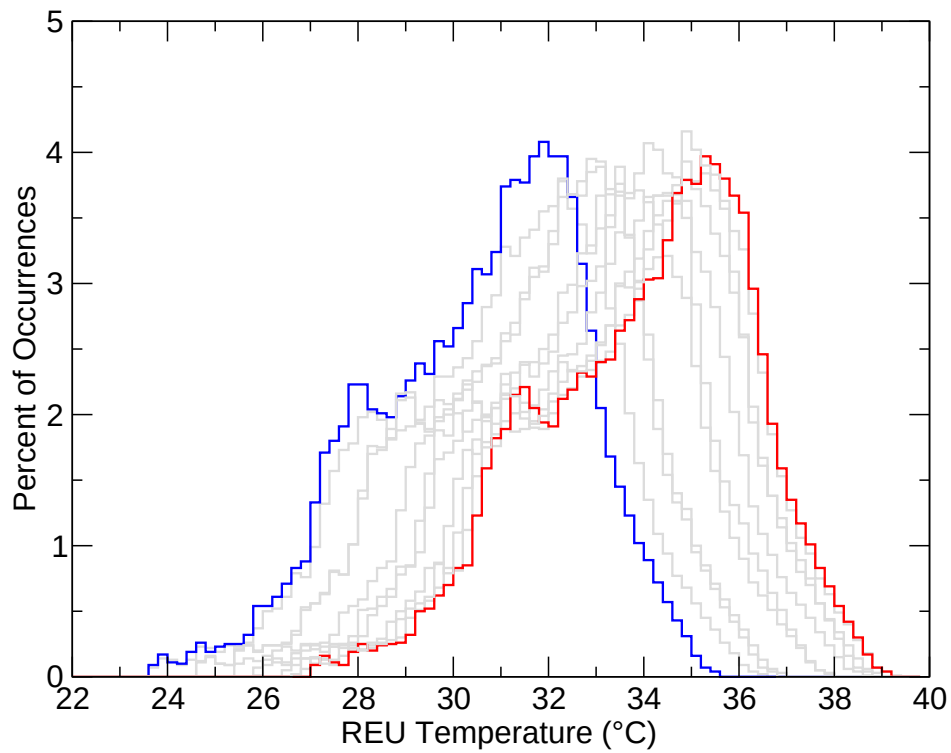


Fig. 4 — Distribution of REU temperature over the WindSat mission. Blue is for the 10.7 GHz V and H polarization REU and red is for the 37 GHz P and M polarization REU in 0.2 deg C bins. The remaining channels are shown in gray and exhibit similar shapes but are bounded by the 10.7 GHz V and H polarization and 37 GHz P and M polarization under normal WindSat operating conditions.



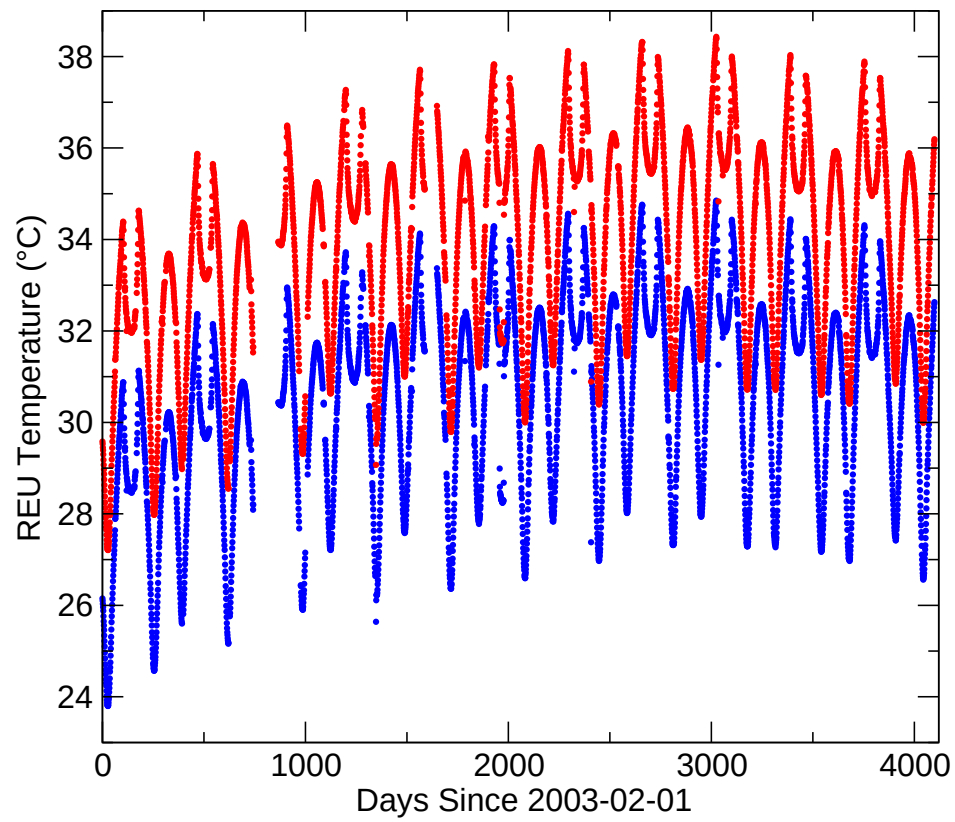


Fig. 5 — The daily mean REU temperature for 10.7 GHz V and H polarizations in blue and 37 GHz P and M polarizations in red from 2003-02-01 to 2014-04-23.

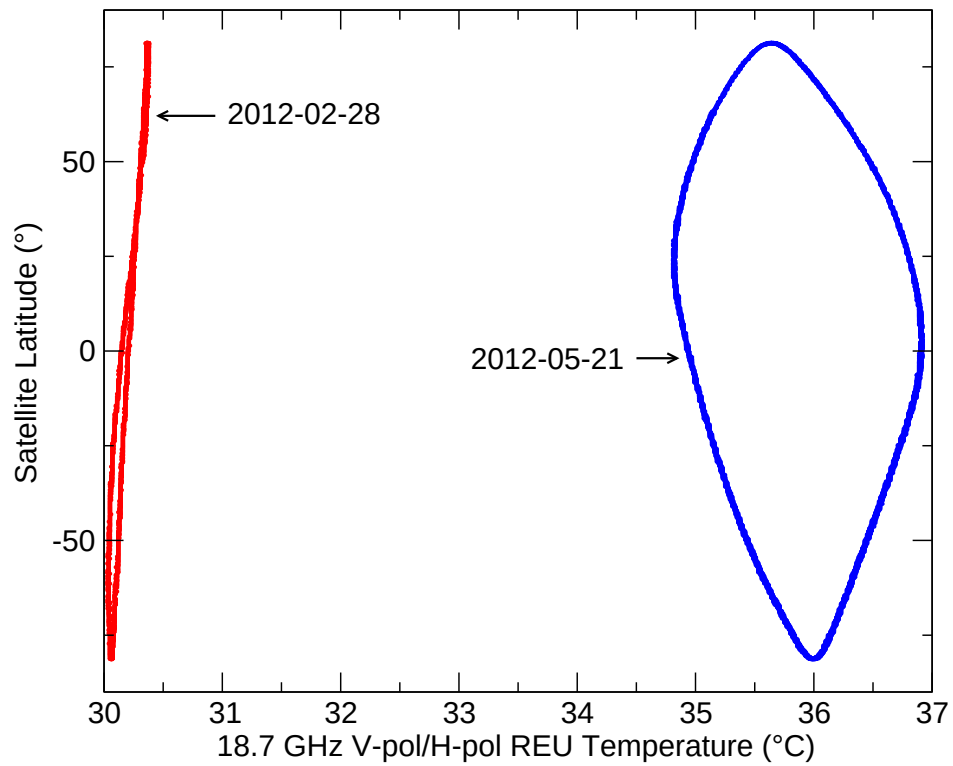


Fig. 6 — The REU temperature for the 18.7 GHz V and H polarizations for two orbits showing the change in temperature variation over the orbit. An orbit from 2012-02-28 is shown in red and an orbit from 2012-05-21 is shown in blue from 2012-05-21.