SATELLITE ATTITUDE ANALYSIS USING THE VICARIOUS COLD CALIBRATION METHOD FOR MICROWAVE RADIOMETERS

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ABSTRACT

A method for estimating the pitch and roll errors of a satellite with an onboard conical scanning microwave radiometer is described. The method makes use of the vicarious cold calibration algorithm which derives a stable cold brightness temperature (TB) over ocean. This cold TB is sensitive to the Earth Incidence Angle (EIA) of the radiometer. Given no pitch or roll errors, the EIA can be modeled as a function of the Earth radius and altitude of the satellite. Deviation from this EIA can then be used to estimate the pitch and roll errors. The pitch/roll algorithm is applied to the current spaceborne microwave radiometer WindSat to show its performance, and the results are compared to the derived pitch and roll of WindSat that are found using a different attitude analysis method.

***Index Terms*—**Calibration, Microwave radiometry

1. INTRODUCTION

Measurements made by spaceborne microwave radiometers are sensitive to the attitude of the satellite. Satellites have onboard attitude control systems; however, a satellite can have small offsets in its pitch, roll, or yaw. These small offsets noticeably affect the brightness temperature (TB) measured by the radiometer onboard the satellite and must be accounted for when analyzing the data. Conical scanning microwave radiometers have a reflector antenna that is offset from nadir which is kept at a constant angle as they scan. The observed TB is a function of the Earth Incidence Angle (EIA), which is the angle the reflector projects onto the surface of the Earth as measured from zenith. Due to the curvature of the Earth, the EIA is not just equal to the off-nadir angle of the reflector antenna. It is a function of the altitude of the satellite as well as the radius of the Earth, as shown in Figure 1.

If there is no pitch or roll of the satellite, the spin axis of the radiometer is oriented vertical with respect to the Earth's surface. On a spherical Earth, the path the radiometer traces out on the surface in this case would be a circle, resulting in a constant EIA over the scan. However, the Earth is slightly oblate, meaning that the radius of the Earth changes with latitude. This will have a small effect on changing the EIA across the scan, as well as throughout the orbit. Also, if the satellite orbit is not perfectly circular, the altitude of the satellite will change throughout the orbit, affecting the EIA. Accounting for the oblateness of the Earth and the altitude of the spacecraft allows a nominal EIA to be calculated for a 0° pitch and roll offset. When a pitch or roll offset of the satellite is introduced, the spin axis of the radiometer is no longer oriented vertically, which means that the true off-nadir angle is no longer equal to the off-nadir angle of the reflector and will change as the radiometer scans. This will cause the EIAs to change as a function of the scan position with respect to the nominal EIA. This deviation from the nominal EIA can be used to calculate the pitch and roll offset of the satellite.

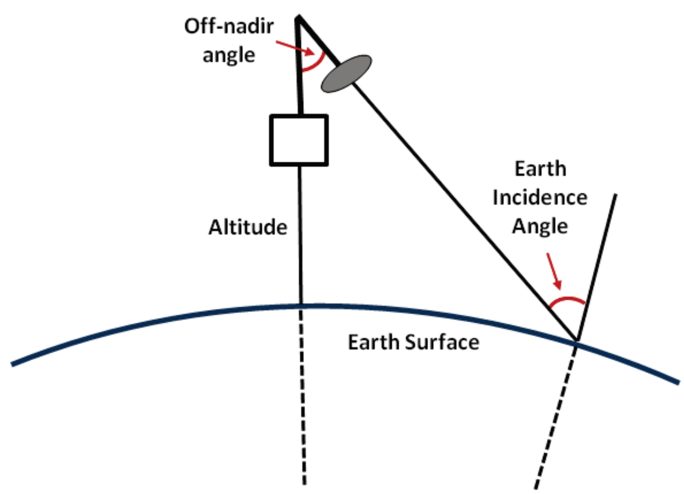

Figure 1: Geometry of the EIA for a spaceborne microwave radiometer.

Typical methods for obtaining the pitch and roll offset of the satellite by a microwave radiometer include geolocation analysis and over-ocean scan biases. Examples of these methods applied to the WindSat radiometer and the Special Sensor Microwave Imager/Sounder are described in [1-3]. This paper presents a method for deriving the pitch and roll offset of the satellite by using vicarious cold calibration [4]. The vicarious cold calibration algorithm is used to find the coldest TBs observed by a microwave

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radiometer. These TBs occur over the ocean with calm winds and minimal atmospheric contribution to the brightness. In these conditions, the TB is dominated by the surface signal which is a strong function of EIA over the ocean. Since EIA is directly related to the attitude of the satellite, the cold cal TB is a useful tool for determining the pitch and roll offset of a satellite with a microwave radiometer onboard.

2. PITCH/ROLL RETRIEVAL ALGORITHM

A minimum squared error retrieval method is used to compute the pitch and roll offsets of the satellite from the cold cal TB across the scan. This is done by minimizing the difference between the observed cold cal TB and the modeled cold cal TB until the retrieved pitch and roll converge to within an acceptable error, which is taken here to be 0.01°. The observed cold cal TB is derived from a radiometer's TBs and the modeled cold cal TB is derived from a Radiative Transfer Model (RTM). The calculation of the observed and modeled cold cal TBs along with a description of the RTM are given in [5]. The modeled TBs are created by assuming that the satellite has a pitch and roll offset that are both 0°. In order to calculate the EIA that is input to the RTM, it is necessary to know the altitude of the satellite as well as the radius of the Earth. The altitude of the satellite is obtained from satellite telemetry. The Earth can be modeled as an oblate spheroid with the radius of the Earth changing as a function of the latitude [6]. This generates a modeled cold cal TB at the nominal EIA that includes altitude and Earth oblateness effects, from which a pitch and roll offset that matches the observed cold cal TB can be found.

The rotational transformations that are required to derive the true off-nadir angle as a function of the scan position for a given pitch and roll are given in [7]. These transformations calculate the true off-nadir angle given a pitch, roll, yaw, elevation angle, and azimuth angle. The elevation angle and the azimuth angle describe the pointing of the radiometer instrument with respect to the satellite coordinate system. The elevation angle is the off-nadir angle of the radiometer reflector measured from vertical, and the azimuth angle describes each scan position. The convention for the sign of pitch and roll is shown in Figure 2. A positive pitch is upward, and a positive roll is clockwise rotation (when looking in the forward direction of the satellite). The yaw of the spacecraft is assumed to be 0°. A downside of using vicarious cold calibration for satellite attitude analysis is that a yaw offset cannot be retrieved. On a spherical Earth, a yaw offset does not affect the EIA since the EIA is constant for all latitudes. On the real Earth, a yaw offset will cause the EIA to change slightly due to Earth's oblateness; however, this EIA change is too small to be detected by the cold cal TB.

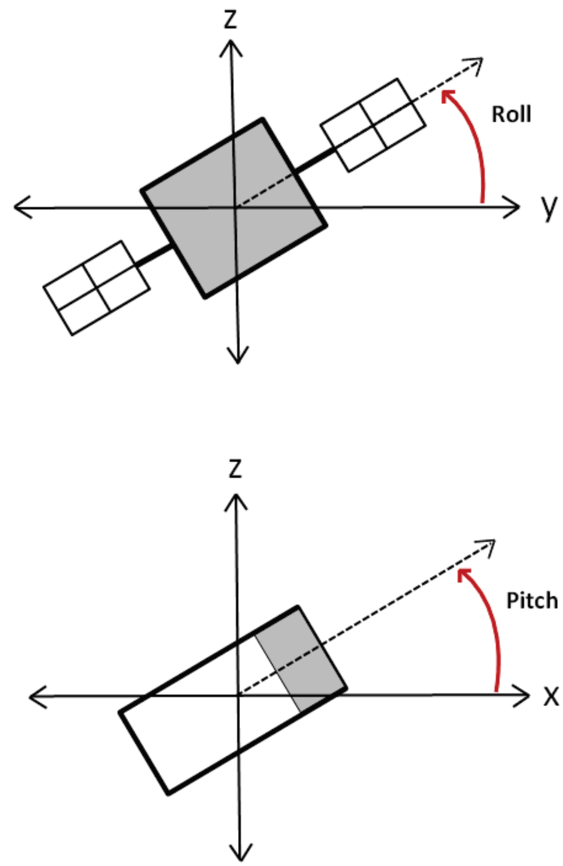

Figure 2: Positive pitch and roll angles of a satellite. The gray shaded area indicates the front of the satellite, i.e the forward-looking side of the satellite.

3. APPLICATION TO WINDSAT

The pitch/roll retrieval algorithm is applied to the WindSat radiometer [8] to analyze how well the algorithm performs. Pitch and roll values have been calculated for WindSat using the geolocation method and over ocean scan biases [1,2], providing a means by which to evaluate our method.

Figure 3 shows the cold cal TB across scan as derived from WindSat observations over a year of data from July 2005 – June 2006 for the 10.7 GHz vertically polarized (V-pol) channel. The 10.7 GHz channel is chosen due to the minimal contribution from the atmosphere relative to the remaining channels. Furthermore, vertical polarization is chosen since it is more sensitive to EIA changes than horizontal polarization. There is a clear scan bias in the cold cal TB as shown in Figure 3 which is due to EIA variability across the scan.

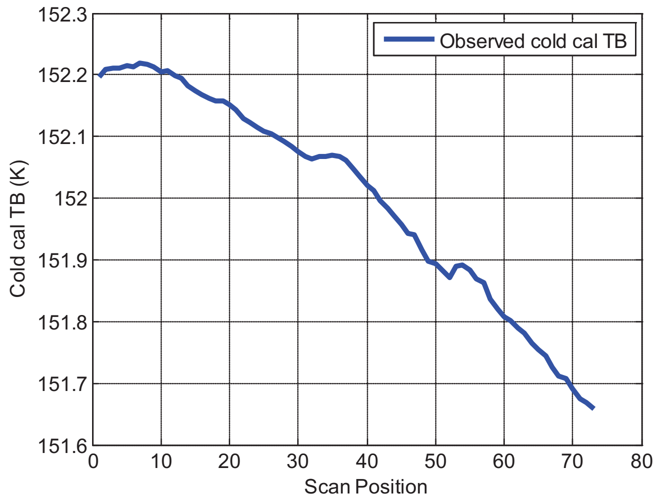

Figure 3: Observed cold cal TB across the scan for the WindSat 10.7V GHz channel.

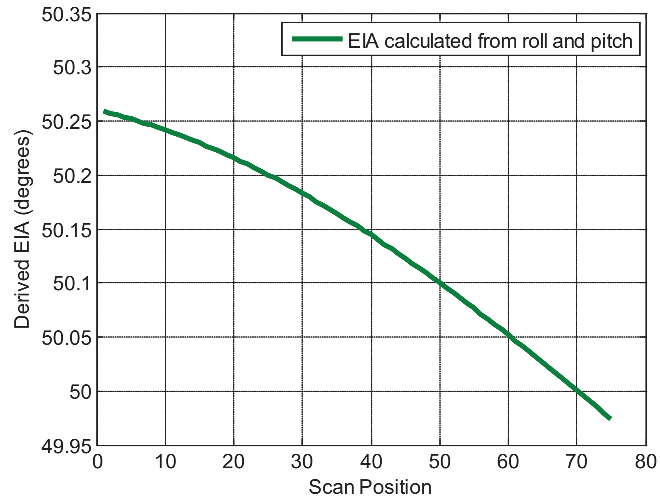

Figure 5: EIA across the scan for a derived pitch of 0.18° and roll of -0.21° for the WindSat 10.7V GHz channel at an altitude of 830 km.

Figure 4 shows the modeled cold cal TB with the derived pitch and roll offset along with the observed cold cal TB and the modeled cold cal TB with no pitch or roll offset. The retrieved pitch and roll offsets are 0.18° and -0.21°, respectively. WindSat scans from right to left and is located on the forward-looking side of the satellite, so the sign convention for the azimuth angle is +34° at scan position 1 and -34° at scan position 80. The negative roll offset implies that the EIAs should be higher on the right side of the scan compared to the left side, as shown in Figure 5.

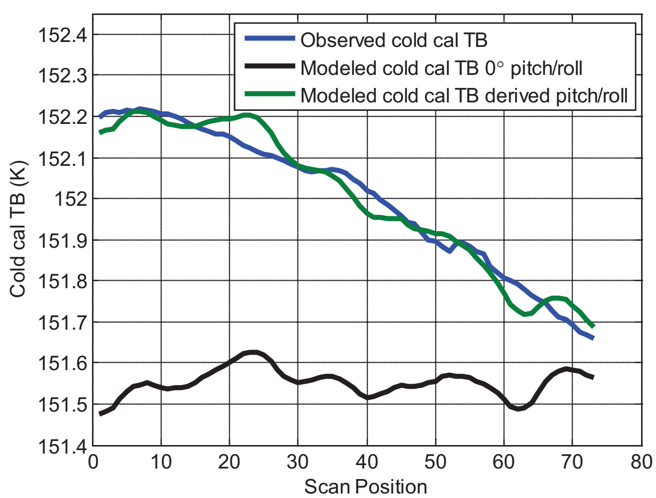

Figure 4: Modeled cold cal TB at 0° pitch/roll with modeled cold cal TB at a pitch of 0.18° and roll of -0.21° compared with the observed cold cal TB for the WindSat 10.7V GHz channel.

The EIA variability seen in Figure 5 is due primarily to pitch and roll offsets. The oblateness of the Earth only contributes <0.01° to changes in the EIA across the scan, which is insignificant when compared to the contribution of pitch and roll offsets to the EIA variability. It is still important, however, to include the Earth oblateness in the model because the changing radius with latitude affects the EIAs throughout the satellite orbit.

The derived pitch and roll offsets found here closely agree with the pitch and roll offsets of [2], who found a pitch of 0.18° and a roll of -0.16° using geolocation.

4. CONCLUSION

A new method for the estimation of the pitch and roll offsets of a satellite with an onboard conical scanning microwave radiometer was presented. The pitch and roll offsets are calculated using the vicarious cold calibration TB from a radiometer's observations. A minimum squared error retrieval method is used to derive a pitch and roll offset based on the scan bias in the observed cold cal TB. This method was applied to the WindSat radiometer and shown to be consistent with another method used to derive the pitch and roll of WindSat through geolocation analysis. One disadvantage to using vicarious cold calibration for attitude analysis is that the yaw offset cannot be retrieved; geolocation analysis is needed if the yaw offset is desired. An important advantage that this method has over using just over-ocean scan biases or geolocation is that the effect of the atmosphere and surface wind speed on the brightness is minimized. The TB across the scan for these conditions over the ocean is dominated by EIA variation, which can be used to derive a pitch and roll offset for the satellite.

5. REFERENCES

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