Algorithms for processing level 1a Tiny Ionospheric Photometer data into level 1b radiances

Overview

This document describes the algorithms for processing Tiny Ionospheric Photometer (TIP) level 1a data into level 1b radiances using the Perl script `tipRadiance.pl` and software provided by the Naval Research Lab (NRL) written in C. Three main codes, `tipstrip.c`, `verniermet.c`, and `product1.c` are called from `tipRadiance.pl` which then reads in the TIP data and interpolates orbit and attitude information to the times of the radiance measurements. The radiance measurement is not a high-quality data product, but more of a quick-look data product. High-quality radiances can require large amounts of massaging involving orbital position, modeled spectral distributions, dark count estimation, etc. The orbit position from the real-time navigation solution usually have an uncertainty of a few tens of meters, but is not checked for outliers.

Input data:

- Level 1a TIP binary data file (`tipBin_YYYY.DDD.LLL.NN_bin`)
  - Time
  - Counts
  - Instrument settings
- Level 1a attitude and orbit data file (`leoAtt_YYYY.DDD.LLL.NN_txt`)
  - Attitude quaternions
  - LEO position and velocity (from real-time navigation solution)
- Calibration file (`tipCal_YYYY.DDD_nml`)
  - Latest updated TIP calibration coefficients
- Measurements file (`tipmeasures.csv`)
  - List and description of telemetry variables used in the TIP data stream
  - Bit positions of all variables
- Extraction file (`extract.txt`)
  - List of desired TIP mnemonics (variables)
- Time data file (`timedata.nml`)
  - Information about leap seconds

  - Launch date and time
  - Time stamp format

- Parameter file (parms#)
  - Settings used for pre-launch test

Output data:

- Level 1b NetCDF file (tipLv1_YYYY.DDD.LLL.NN.SSSS.VVVV_nc)
  - Time of TIP measurement (GPS seconds)
  - TIP Photon count
  - TIP Radiance measurement
  - TIP motor position
  - TIP measurement quality flag
  - Deviation of TIP pointing from nadir
  - TIP ground target latitude and longitude
  - LEO altitude above ellipsoid
  - Latitude and longitude of sub-satellite track
  - Global attributes:
    * Date and time of first observation (GPS time)
    * Times of first and last observations (GPS seconds)
    * Name of TIP calibration file used in the processing

Processing steps:

1. Conversion of TIP raw data counts into radiance as a function of time
2. Calculation of the deviation of TIP pointing from nadir
3. Conversion of TIP pointing unit vector to Earth-fixed reference frame
4. Interpolation of TIP pointing and LEO position to TIP measurement time
5. Calculation of the TIP ground target latitude and longitude
6. Calculation of the LEO altitude, latitude, and longitude

1 Conversion of TIP raw data counts into radiance as a function of time

The binary TIP telemetry file is stripped into comma-delimited data files for each of six TIP subframe types. These files are placed in a temporary directory and read in to memory as needed. The six-month GPS epoch associated with the 24-bit GPS time stamp is calculated, and the synchronization between GPS time and TIP time tags is establised to calculate the Mission Elapsed Time and the GPS time for each sample. The epoch estimate is based upon the date stamp in the data filename.

The 1356 Å radiance is calculated as the rate of the raw counts (raw counts, N, divided by the integration time, Δt) multiplied by a sensitivity factor, S, which is determined from the instrument settings, the filter temperature, and the TIP calibration coefficients:

$$I = S\frac{N}{\Delta t} \ . \tag{1}$$

A quality flag is calculated based on output from the flight controller. Possible values and their meanings are:

0: measurement is good

1: incomplete science sample due to high-voltage fluctuation

3: incomplete science sample because motor was not yet in position

4: ill-defined sensitivity, but a good sample (the count rate is reported in place of radiance)

5: ill-defined sensitivity and incomplete science sample due to high voltage fluctuation

7: ill-defined sensitivity and incomplete science sample because motor was not yet in position

Main programs:

`tipstrip.c` – strips the binary file into Comma Separated Values (CSV) data files for each TIP subframe type.

`verniermet.c` – generates high-precision times for TIP samples and calculates the Mission Elapsed Time (MET) for each sample. Places the result in another CSV data file.

`product1.c` – combines TIP data, vernier time info, and calibration info into 1356 Å radiance as a function of time. Places the result in another CSV file.

Subroutines:

`ReadTip::readCsv` – reads in a CSV data file.

2 Calculation of the deviation of TIP pointing from nadir

The quaternion, $q = q_{\mathrm{w}} + \mathbf{i}q_{\mathrm{x}} + \mathbf{j}q_{\mathrm{y}} + \mathbf{k}q_{\mathrm{z}}$, as a function of time, describes the attitude of the space craft (S/C) relative to the local level (LL) frame. Nominally, the TIP should be pointing downwards in the direction of nadir, which is in the direction of the +z axis of the LL frame. In reality, the TIP points in the direction of the +z axis of the S/C frame. The +z(S/C) direction may be slightly different than the +z(LL) direction because of the varying attitude of the satellite (probably within ±10°). To find the difference, and later to find the TIP ground target location, the +z(LL) unit vector is rotated into the +z(S/C) unit vector using the quaternion:

$$\mathbf{i}z_1 + \mathbf{j}z_2 + \mathbf{k}z_3 = q^*\mathbf{k}q \ . \tag{2}$$

The angle between these two unit vectors (the TIP pointing deviation) is then calculated as $\arccos(z_3)$.

Subroutines:

`ReadAtt::readAtt` – reads in space craft attitude and orbit information from a `leoAtt` file.

3 Conversion of TIP pointing unit vector to Earth-fixed reference frame

The +z(LL) unit vector in Earth-centered fixed (ECF) coordinates is calculated from the LEO position, $\vec{r}$, in ECF coordinates as $-\vec{r}/|\vec{r}|$. The +y(LL) unit vector is defined as $\vec{r} \times \vec{v}/|\vec{r} \times \vec{v}|$, where $\vec{v}$ is the LEO velocity in ECF coordinates. Finally the +x(LL) unit vector is defined as the vector product between the +y(LL) and the +z(LL) unit vectors, forming a right-handed Cartesian coordinate system. Together, these three unit vectors makes a 3×3 coordinate transformation matrix (transforming a vector in LL coordinates to ECF coordinates), and the +z(S/C) unit vector in ECF coordinates is calculated as the martrix-vector product between this matrix and the +z(S/C) unit vector in the LL frame.

4 Interpolation of TIP pointing and LEO position to TIP measurement time

The TIP pointing deviation, the components of the +z(S/C) unit vector (in ECF coordiantes) and the components of the LEO position, are interpolated to the times of the radiance measurements using piecewise cubic Bessel interpolation. Piecewise cubic Bessel interpolation is a special case of piecewise cubic Hermite interpolation. In piecewise cubic Hermite interpolation, the function in each interval between two known points are determined by a third-degree polynomium given by the two known point values and the first-order derivative at each of these points. In piecewise cubic Bessel interpolation the (in principle unknown) derivative at each known point is estimated from a second degree polynomium going through this point and the two neighboring points, one on each side. The end point derivatives are given by the second-degree polynomiums going through the three points closest to each end.

Subroutines:

`Interp::cubicBessel` – Provides piecewise cubic Bessel interpolation of a given 1D grid function onto another given 1D grid.

5 Calculation of the TIP ground target latitude and longitude

The TIP ground target (ECF coordinates) is found as the intersection between the Earth's ellipsoid and a straight line originating from the LEO position in the direction of the +z(S/C) unit vector. In essence the ground target coordinates are found as

$$\vec{r}_{\text{targ}} = \vec{r}_{\text{leo}} + \gamma \vec{z}_{\text{sc}} \ , \tag{3}$$

where γ is the smallest of two roots of a second degree polynomium (the larger root corresponds to the intersection of the line and the ellipsoid on the other side of the Earth). The equation for γ follows from the constraint that $\vec{r}_{\text{targ}}$ needs to be a point on the ellipsoid:

$$\frac{(x_{\text{leo}} + \gamma z_1)^2}{a^2} + \frac{(y_{\text{leo}} + \gamma z_2)^2}{a^2} + \frac{(z_{\text{leo}} + \gamma z_3)^2}{b^2} = 1 \ , \tag{4}$$

where a and b are the Earth's major and minor axis radii.

Finally the ECF coordinates are converted to geographic latitude and longitude on the ellipsoid. For the geographic latitude, λ, we use the relation:

$$\tan\lambda = \frac{a^2}{b^2} \tan\phi \ , \tag{5}$$

where ϕ is the geocentric latitude.

6 Calculation of the LEO altitude, latitude, and longitude

The sub-satellite point, $\vec{r}_{\text{s}} = (x_{\text{s}}, y_{\text{s}}, z_{\text{s}})$, is found as the one satisfying the equation

$$\vec{r}_{\text{leo}} = \vec{r}_{\text{s}} + \eta \vec{n}_{\text{s}} \ , \tag{6}$$

where $\vec{n}_{\text{s}}$ is a vector normal to the ellipsoid at the sub-satellite point:

$$\vec{n}_{\text{s}} = \begin{pmatrix} x_{\text{s}} a^{-2} \\ y_{\text{s}} a^{-2} \\ z_{\text{s}} b^{-2} \end{pmatrix} \ . \tag{7}$$

The equation for η follows from the constraint that $\vec{r}_{\text{s}}$ needs to be a point on the ellipsoid:

$$\frac{x_{\text{leo}}^2}{a^2}\left(1 + \frac{\eta}{a^2}\right)^{-2} + \frac{y_{\text{leo}}^2}{a^2}\left(1 + \frac{\eta}{a^2}\right)^{-2} + \frac{z_{\text{leo}}^2}{b^2}\left(1 + \frac{\eta}{b^2}\right)^{-2} = 1 \ . \tag{8}$$

The multiplier η is found by iteration using Newton-Raphson's method. Then $\vec{r}_{\text{s}}$ is determined from (6), and the altitude of the LEO satellite above the ellipsoid is calculated as $h = \eta |\vec{n}_{\text{s}}|$. Finally, the ECF coordinates of the sub-satellite point are converted to geographic latitude and longitude.