Readme for GOES-R L2 Ephemeris Data

Stefan Codrescu and Janet Machol

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1 Summary

The GOES-R series is a set of satellites situated in geostationary orbit with one operational satellite at 75.2°W and one at 137.2°W. The series consists of the GOES-16, -17, -18, and -19 satellites. The Level 2 (L2) ephemeris product (ephe-l2-orb1m) provides the precise position of each satellite at a 1-minute cadence in the following coordinate frames: Cartesian Earth Centered Earth Fixed (ECEF), spherical geographic (GEO), and Cartesian Geocentric Solar Ecliptic (GSE). Local time at the satellite is also given. The data product is available in NetCDF format and is produced by NOAA's National Center for Environmental Information (NCEI). The data is provided in files for daily, annual, and mission aggregations.

This Readme gives brief descriptions of the ephemeris product, error analysis, and data processing. The data and documentation can be found at

`https://www.ncei.noaa.gov/products/goes-r-extreme-ultraviolet-xray-irradiance`.

Users of the data are responsible for inspecting the data and understanding the caveats prior to use. Questions about this data can be sent to *swx.irradiance@noaa.gov*.

2 Ephemeris Product Overview

The variables provided in the ephe-l2-orb1m product are listed in Table 1.

Table 1: Summary of the ephe-l2-orb1m product contents.

Variable	Coordinate System	Description
time	–	Record start timestamps at a 1-min cadence.
ecef_xyz	ECEF	(Earth-Centered Earth-Fixed) Cartesian system that rotates with the Earth.
geo_llr	GEO	(Geographic) Spherical latitude, longitude, and radius from the center of the Earth.
gse_xyz	GSE	(Geocentric Solar Ecliptic) The GSE X-component is along the Earth - Sun line, the Z-component is along the ecliptic normal, and the Y-component forms the right-handed basis in the dusk direction.
local_time	GEO	Local time in hours, based on spacecraft longitude.
gse_local_time	GSE	GSE local time in hours.
flags	–	Indicates missing and interpolated points.

More information about GSE and GEO coordinates is available from `https://www.mssl.ucl.ac.uk/grid/iau/extra/local_copy/SP_coords/geo_sys.htm` and [3, 5]. The timestamps provided are record start times; the timestamp is at the beginning of the minute, and the value is valid over the following minute interval. The associated location data gives the position of the spacecraft in the middle of the record.

The time variable, $time[secs] = Time[UTC] - base_time[UTC]$, is an elapsed time in units of "secs since *base_time*" where *base_time = 2000-01-01 12:00:00[UTC]* and was calculated without including leap seconds that occurred since 1 Jan 2000. Time stamps can be calculated by the user in Coordinated Universal Time (UTC) as

$$Time[UTC] = base_time[UTC] + time[secs] + n[secs] \tag{1}$$

where $n = 0$ for a time conversion function which ignores leap seconds (e.g., Python cftime.num2date or netCDF4.num2date) and $n = number\ of\ leap\ seconds\ since\ base_time$ if the function includes leap seconds. It should be noted that the reference epoch of "2000-01-01 12:00:00 UTC" is not the same as the J2000 epoch, because the latter is given in terrestrial time (TT) units which differ by more than a minute from UTC. For a table of leap seconds, see `https://www.nist.gov/pml/time-and-frequency-division/time-realization/leap-seconds`.

Local time, which is based on the GEO longitude, is defined as

$$\text{local_time} = \text{time} + \frac{\text{geo_longitude}}{15} \mod 24 \tag{2}$$

GSE local time is defined as

$$\text{gse_local_time} = \left(12 \cdot \frac{\arctan2(\text{gse_y}, \text{gse_x})}{\pi} + 12\right) \mod 24 \tag{3}$$

The difference between GSE local time and satellite time varies on a daily cycle with a total magnitude of approximately ±16 minutes (Figure 1). Over the course of a year, the phase of this cycle drifts, while the magnitude of the cycle varies by less than 1%. By definition (Equation 2), the offset of GSE local time from local time also follows this pattern. Because of the annual drift in the daily cycle, the offset between GSE and GEO local times at a particular time (e.g., local midnight) varies on an annual cycle with a magnitude of less than 15 minutes (Figure 2).

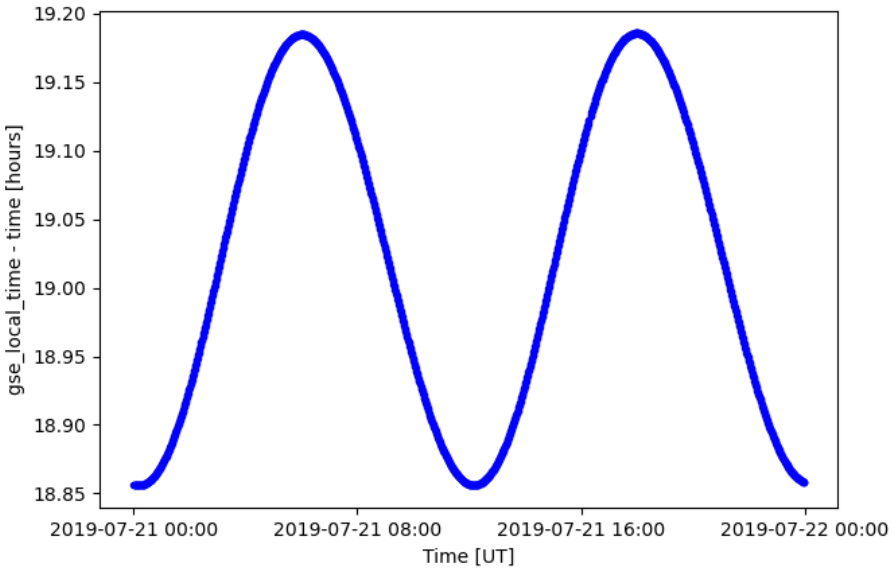

Figure 1: The difference between GSE local time and satellite time for GOES-16 on 21 July 2019.

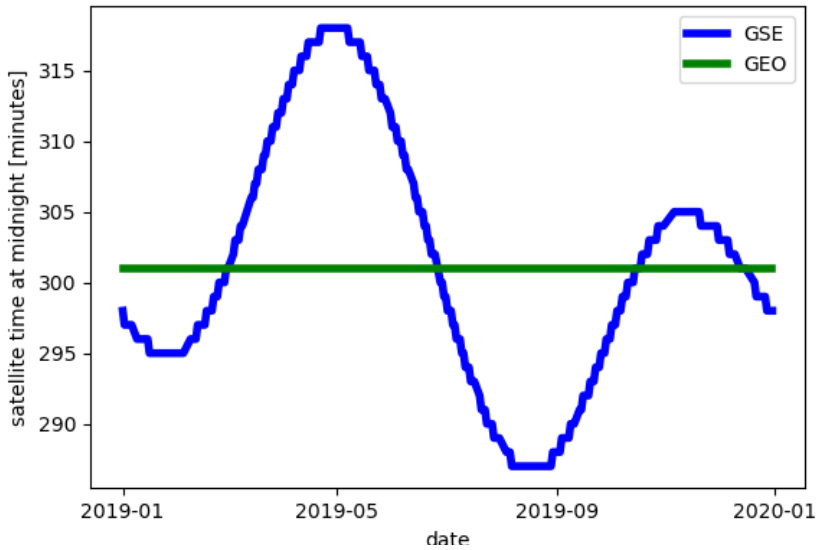

Figure 2: GOES-16 satellite time (minute of the day) when GSE and GEO local time is midnight (00:00) for the year 2019. Time resolution is 1 minute.

3 Data Processing Details and Accuracy Estimates

The satellite position is derived from an on-satellite GPS receiver. The position is accurate to within 15.2 m for 99% of the time [6]. Rotations between coordinate frames introduce numerical errors.

For GOES-16 and GOES-17 data, from the beginning of each mission until 2021-06-30, the ephe-l2-orb1m product is derived from the Level 0 (L0) telemetry data which provides the position in the Earth Centered Inertial (ECI) coordinate frame derived from an on-board GPS receiver. The ECI coordinates are rotated to the ECEF reference frame using the Astropy software library [1, 2]. The ECEF coordinates are rotated to GEO coordinates using the Cartesian-to-spherical conversion and to GSE coordinates using the Spacepy software library [4].

After 2021-06-30, the ephe-l2-orb1m product is derived from ECEF_{X, Y, Z} variables from the Level 1b (L1b) magn-l1b-geof product. There were two issues with the L1b ECEF data prior to this date. The first issue was incorrect ECEF variable contents early in the mission. The second issue was an overly narrow valid_range metadata attribute for the ECEF_Z variable, which caused data for portions of each day to be masked. The metadata has been corrected in v0-0-0 operational L1b dayfiles for 2021-07-01 and onward, and for science-quality EXIS L1b dayfiles. The metadata correction will be retroactively applied to all L1b data in a future version of the L1b dayfile products. Using ECEF coordinates obtained from L1b data, the procedure to calculate GEO and GSE coordinates is the same as from L0 data as described above.

Comparisons between L1b ECEF and ECEF derived from L0 ECI show agreement of better that 10 m (Figure 3).

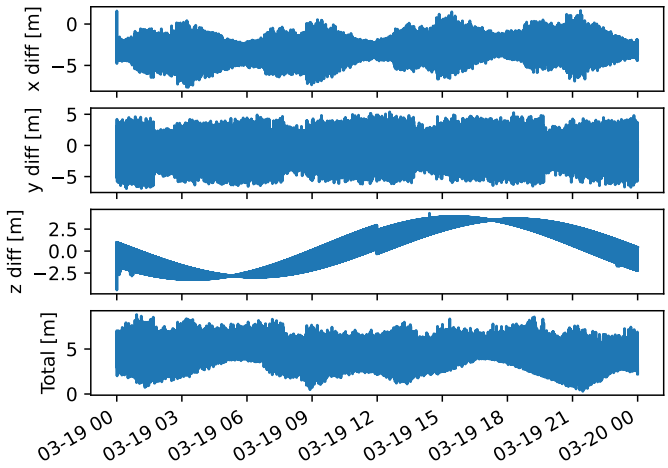

Figure 3: The difference between L1b ECEF and L0-derived ECEF (L1b - L0) is shown for each component and the magnitude of the difference vector. The independent implementations of ECI to ECEF agree to within 10 m.

Missing ECEF components are linearly interpolated for up to 30 minutes for this product. If the satellite position is missing for more than 30 minutes, no interpolation is performed and the data will be set to fill values. Interpolation over 30 minutes is expected to generally introduce no more than 90 m of error from the true position as discussed in Appendix A. The ephe-l2-orb1m product is time gridded, so there will be a value for each minute of the day – either a valid position, or a fill value. Interpolated and missing values are flagged. In the rare cases where all of the contents would be fill values, then the dayfile is not produced.

The conversion from ECEF to GEO coordinates uses traditional Cartesian to spherical formulae; e.g., see `https://en.wikipedia.org/wiki/Spherical_coordinate_system#Cartesian_coordinates`. This transformation neglects the non-spherical flattening of the Earth. To account for flattening, Bowring's method (`https://www.mathworks.com/help/aeroblks/ecefpositiontolla.html`) could be used to calculate a more accurate latitude. However, flattening has a negligible impact on the latitude calculation at the equator. Since GOES-R series satellites are in geostationary orbit near the equator, we believe this is an appropriate simplification. Bowring's method simplifies to the traditional formulae when the flattening coefficient is set to 0.

4 Versions

Version numbers for the ephe-l2-orb1m product are listed in Table 2.

Table 2: ephe-l2-orb1m versions.

Version	Release date	Revisions
0-0-3	21 April 2023	Time variable description references leap seconds.
0-0-2	15 Jan 2022	Initial public data release.

References

[1] Astropy Collaboration et al. "Astropy: A community Python package for astronomy". In: *Astronomy and Astrophysics* 558, A33 (Oct. 2013), A33. DOI: 10.1051/0004-6361/201322068. arXiv: 1307.6212 [astro-ph.IM].

[2] Astropy Collaboration et al. "The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package". In: *Astronomical Journal* 156.3, 123 (Sept. 2018), p. 123. DOI: 10.3847/1538-3881/aabc4f. arXiv: 1801.02634 [astro-ph.IM].

[3] M. Kivelson and C. Russell. *Introduction to Space Physics*. Cambridge atmospheric and space science series. Cambridge University Press, 1995. ISBN: 9780521457149. URL: https://books.google.com/books?id=qWHSqXGfsfQC.

[4] B. A. Larsen et al. *SpacePy*. DOI: 10.5281/zenodo.3252523. URL: https://doi.org/10.5281/zenodo.3252523.

[5] Thompson, W. T. "Coordinate systems for solar image data". In: *A&A* 449.2 (2006), pp. 791–803. DOI: 10.1051/0004-6361:20054262. URL: https://doi.org/10.1051/0004-6361:20054262.

[6] S. Winkler et al. "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft". In: *Proceedings of the 10th International ESA Conference on Guidance, Navigation & Control Systems*. Salzburg, Austria, 2017. URL: https://ntrs.nasa.gov/citations/20170004849.

Appendix A Interpolation Error

The interpolation error was bounded by examining GOES-16 ECEF positions on 2021-03-19. Each possible segment of 30 minutes during the day was replaced with a linear interpolation of the values surrounding the segment, then compared against the original observed values. Figure 4 shows the maximum Euclidean distance between interpolated versus observed values, for each possible offset of the 30 minute interpolated segment through the day. The analysis for this day shows a maximum error of less than 90 m introduced by the 30 minute interpolation window. The double peak shape is expected because GOES-16 traces a figure 8 shape in ECEF coordinates (i.e., as viewed from the ground). The two peaks of maximum error are caused by linear interpolating over the most curved portions of the orbit.

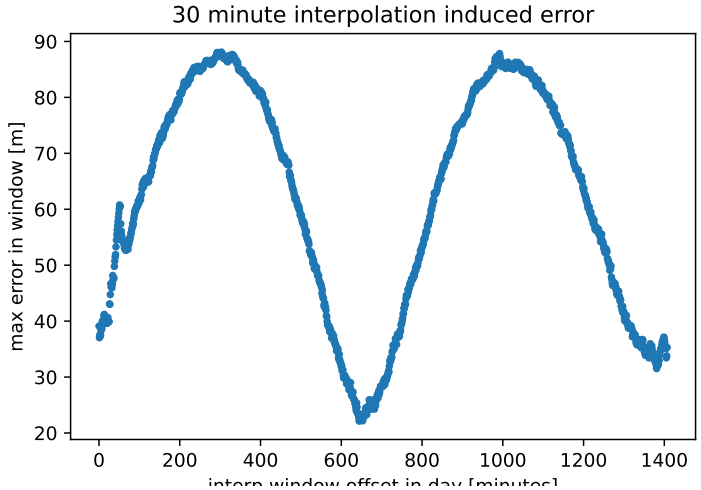

Figure 4: Maximum Euclidean distance between interpolated versus observed values over 30-minute segments of ECEF positions for GOES-16 on 2021-03-19.

The maximum error can be plotted as a function of window size (Figure 5), showing an expected increase

in potential error as the interpolation window size increases.

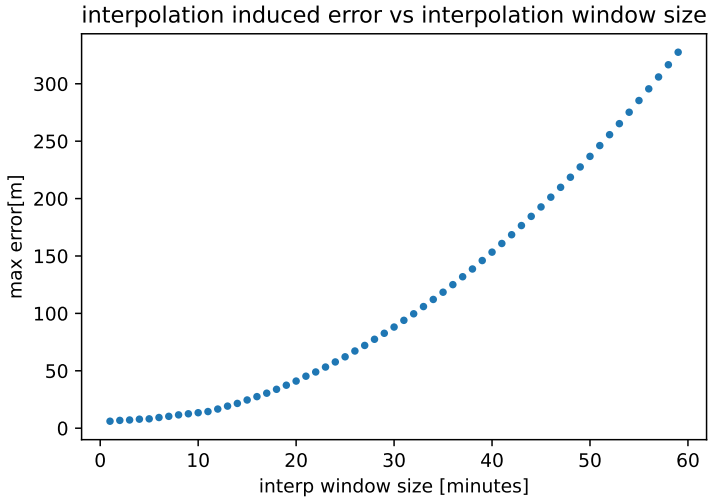

Figure 5: The maximum interpolation error plotted as a function of interpolation window size.

To ensure that 90 m is a typical estimate of the maximum interpolation error on all days, the analysis performed for 2021-03-19 (Figure 4) was repeated for all days with valid data between 2017-01-01 and 2021-01-01. The resulting daily min and max error due to linear interpolation over a 30 minute segment is plotted in Figure 6. Although the maximum error induced by 30 minute interpolation is less than 90 m for almost all days, there are a small number of days where the error could be greater than 1 km. In applications that are very sensitive to the spacecraft location, we recommend that the user inspect the flags for interpolated data and pick their own tolerance for the maximum interpolated gap width.

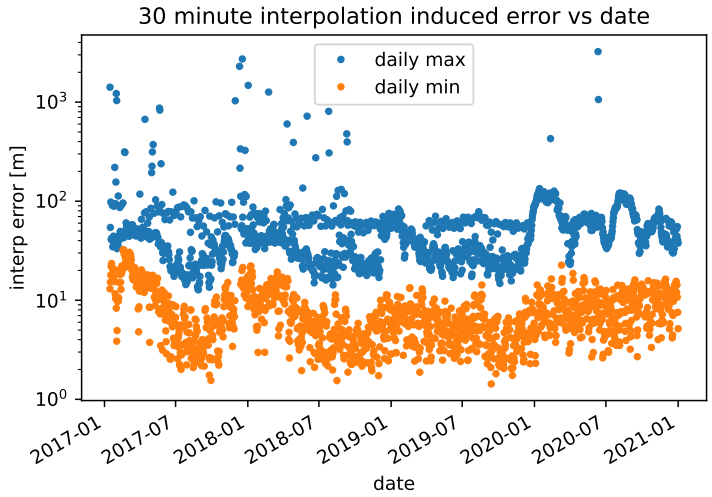

Figure 6: Daily maximum and minimum Euclidean distance between interpolated versus observed values over 30-minute segments of ECEF positions for GOES-16.