Spire Level 1 RO Excess Phase Product Description

Spire Global Inc.

Issue/Revision	***Date***	***By***	***Description***
1.0	2021-08-19	Spire	Initial version

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1 Overview

Spire *atmPhs* files contain ground-calibrated measurements of atmospheric excess phase delay during radio occultation events. They primarily serve as intermediate level (Level 1B) data products in the radio occultation retrieval processing chain. However, *atmPhs* files also contain geophysical information about the ionosphere during radio occultation events because they often span an altitude range that exceeds 140 km above the Earth's surface.

This document provides an overview of the processing and file contents of Spire's *atmPhs* product.

2 Processing

2.1 Provenance

The atmPhs product is derived from data contained in the following Spire products:

- Raw occulting phase observations: *rocObs*
- Raw reference phase observations: *rocRef*
- Precise orbit estimates of the Spire satellite: *leoOrb*
- Spire satellite attitude quaternions: *leoAtt*
- Spire receiver phase center offsets: Receiver ANTEX

External data used to derive Spire's *atmPhs* product are listed below:

- GNSS orbit positions from an external provider
- GNSS transmitter phase offsets from IGS

2.2 Description

GNSS signals traversing the Earth's atmosphere during RO events are collected by Spire's receiver in low-Earth orbit using an open-loop tracking technique. The raw, open loop phase measurements and a-priori model estimates are recorded and downlinked to the ground as *rocObs* files, forming the beginning of the RO processing chain. In order to derive atmospheric profiles of bending angle and refractivity from these raw measurements, the excess phase delay induced by the Earth's atmosphere must be derived for each time stamp.

The equation below shows how the excess phase in unit distance at each time step during the occultation event can be estimated given the total carrier phase measurement, (ϕ), the geometric delay between the GNSS transmitter and Spire receiver (R), and clock errors multiplied by the speed of light ($c * [\Delta clock]$).

$$\Delta excess\ phase\ =\ \varphi\ -\ R\ -\ c\ *\ [\Delta clock] \qquad \text{Eq. 1}$$

The total phase of the occulted GNSS signal is a combination of two quantities: the a priori open loop model and the in-phase and quadrature (Q) components of the residual phase. It can be reconstructed using the following equation for each GNSS wavelength (λ):

$$\varphi\ \equiv \left(OL_{Model} -\ arctan2(Q,\ I)\ /\ (2\pi)\right) *\ \lambda\ [m] \qquad \text{Eq. 2}$$

Because the residual phase measurements are derived by taking the arctangent of the open loop in-phase and quadrature samples, the total phase quantities contain 2π discontinuities. Furthermore, the total phase may be modulated by navigation data bits depending on the GNSS frequency used, which manifests as π discontinuities. Phase unwrapping and navigation data bit removal are not currently performed during Spire excess phase processing and are left to downstream users to perform based on their application.

The geometric delay (R) in Eq. 1 is defined as the straight-line distance between the GNSS transmitter phase center at transmit time and the Spire receiver phase center at receive time. Phase center locations are estimated given the GNSS and Spire satellite center-of-mass of locations derived from precise orbit determination, the phase center offsets in the spacecraft body frame, and satellite attitude information.

Clock errors that must be corrected to precisely estimate atmospheric excess delay include the receiver clock error, transmitter clock error and relativistic effects. Effects of the receiver clock error are removed using high-rate phase measurements simultaneously collected from a reference GNSS satellite (*rocRef*) during a RO event. Since the receiver clock errors are common to both the reference and occulting observations, they can be removed by subtracting the calibrated reference observations from the primary occulting link observations (e.g. single differencing). Unlike the receiver clock error, the GNSS transmitter clock error is removed directly from estimates made available by an external provider. Finally, smaller relativistic effects are corrected using the satellite orbit positions and velocities.

The main outputs of the excess phase processing step of an occultation event are illustrated in Figure 1. The top plot shows the excess phase delay over an occultation duration of about 2.5 minutes. In this setting occultation scenario, the tangent point of the GNSS signal descends through the atmosphere over time. Because the density of the atmosphere increases with decreasing altitude, the excess phase delay increases over the course of a setting occultation event. Although not discernible from the plot, the excess phase delay is dependent on the transmitted GNSS carrier frequency (e.g., GPS L1 at 1575.42 MHz vs. GPS L2 1227.60 MHz). This is because the signal also passes through the ionosphere region which imparts frequency-dependent phase delays.

In the bottom plot of Figure 1, the signal-to-noise ratio (SNR) is plotted versus straight line height, defined as the tangent point altitude of the occulted signal. The SNR remains constant at the beginning of the occultation until it descends below 40 km altitude. As the signal passes through the troposphere (below 10 km altitude), the signal undergoes large fluctuations in amplitude primarily caused by the presence of water vapor. The plot also shows signal amplitude fading at straight line height below 0 km. This phenomenon is attributed to the large bending of the GNSS signal as it travels through the lowest and densest portions of the atmosphere.

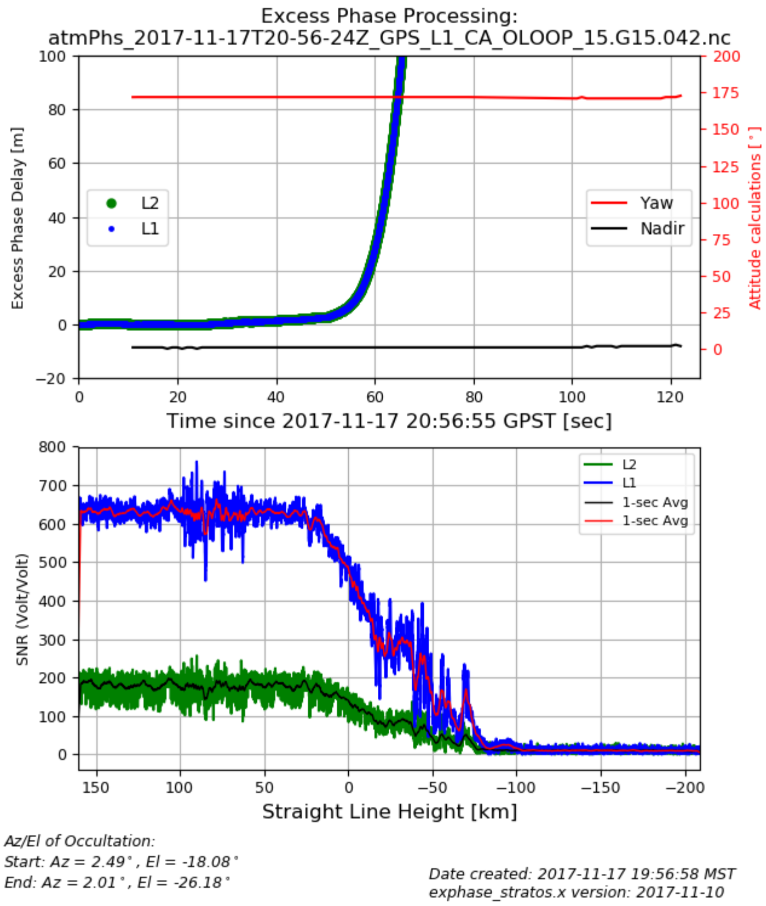

Figure 1*: Output data from the excess phase processing step. The top plot shows the excess phase delay on the L1 and L2 frequencies as a function of time while the bottom plot shows the L1 and L2 SNR as a function of straight line height during the occultation event. Additionally, there are two lines (red, black) in the top plot which represent the pointing stability of the spacecraft during the occultation event.*

3 Product Content

3.1 Overview

The following describes the content of Spire's *atmPhs* product. The file format is similar to the one used by the COSMIC Data Analysis and Archive Center (CDAAC) for the COSMIC-1 radio occultation mission.

3.2 Naming Convention

Each *atmPhs* file has the following naming convention:

spire_gnss-ro_L1B_atmPhs_{VERSION}_{OCC_TIME}_{FM}_{RINEX_ID}.nc

where

*VERSION***:** Product version (e.g. v6.02)

OCC_TIME: Occultation time of event (i.e 2020-01-01T00-00-00). Occultation time is equivalent to the first time stamp of the input L1 *rocObs* file used in excess phase processing.

FM: Spire satellite id (e.g. FM103)

RINEX_ID: GNSS RINEX ID (i.e G01)

3.3 File Observational Coverage

Each *atmPhs* file typically contains occulting link measurements for several minutes that cover a tangent height altitude range spanning from approximately -200 km to 170 km above the surface of the Earth. However, this altitude range can vary according to a number of factors:

- **Duration of the raw occulting measurements**: Some occultation events may be truncated due to satellite yaw maneuvers or receiver powering off.
- **Reference link observational coverage**: There may be gaps in the reference satellite observational coverage that cause the *atmPhs* file to start late or end early relative to the occulting measurement collection time period.
- **On-board scintillation measurements:** As of 2021, the receiver constantly monitors high scintillation events using an onboard detector. When a large

scintillation event is detected, the receiver will download all high-rate raw phase data spanning from orbit altitude (0° elevation) and downward, which greatly expands the typical atmPhs altitude range.

3.4 Notable Variables

Format: NETCDF

*Note: A complete list of global attribute variables can be found at https://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=atmPhs
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Variable	Dimension	Source	Description	Unit
time			Time since the start time of the occultation event	sec
exL1	time	Derived	Atmospheric excess phase delay on L1 frequency	meters
exL2	time	Derived	Atmospheric excess phase delay on L2 frequency	meters
caL1Snr	time	Derived	1-sec accumulated signal to noise ratio on the L1 channel derived from the amplitude of the residual phase values and estimated noise floor values. See Appendix A of Spire Level 0 Raw RO Product Description.	0.1 V/V
pL2Snr	time	Derived	1-sec accumulated signal to noise ratio on the L2 channel derived from the amplitude of the residual phase values and estimated noise floor values. See Appendix A of Spire Level 0 Raw RO Product Description.	0.1 V/V
x(yz)Leo	time	Derived	X(YZ) position of the receiver antenna phase center at received time in the Earth Centered Inertial frame (rotated from ITRF frame accounting only for GMST)	km
x(yz)dLeo	time	Derived	X(YZ) velocity of the receiver antenna phase center at received	km/s

			time in the Earth Centered Inertial frame (rotated from ITRF frame accounting only for GMST)	
x(yz)Gps	time	Derived	X(YZ) position of the GNSS transmitter antenna phase center at transmit time in the Earth Centered Inertial frame (rotated from ITRF frame accounting only for GMST)	km
x(yz)dGps	time	Derived	X(YZ) velocity of the GNSS transmitter antenna phase center at transmit time in the Earth Centered Inertial frame (rotated from ITRF frame accounting only for GMST)	km/s
txTime	time	Derived	Time of GNSS satellite transmission (since start of occultation)	sec
exrefL3	time	Derived	Excess phase for ionospheric-free reference link (interpolated)	meters

Notable Global Attributes

Attribute	**Description**
startTanheight	Straight line tangent height of the occulting link at the beginning of the file
endTanheight	Straight line tangent height of the occulting link at the end of the file
noise_l1_applied	Noise value applied to derive L1 SNR
noise_l2_applied	Noise value applied to derive L2 SNR