The STAR GNSS Radio Occultation 1DVAR Version 1.0 Data Product User Guide

NOAA/STAR GNSS RO Team

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1. Introduction

The STAR Global Navigation Satellite System (GNSS) Radio Occultation (RO) one-dimension variational inversion algorithm (1DVAR) software package is developed to retrieve atmospheric pressure, temperature, and water vapor from the refractivity obtained in RO observations. Input refractivity is taken from RO atmPrf files. RO atmPrf file includes RO bending angles, impact parameters, tangent point location, quality information, as well as refractivity. Currently, we use RO atmPrf generated by University Corporation for Atmospheric Research (UCAR) operational data processing center and distributed by COSMIC Data Analysis and Archive Center (CDAAC). In the future, we could use RO atmPrf files generated by the STAR GNSS RO team. The main output is collected in NetCDF files (one for each RO measurement). To be consistent with the name conversion from other RO processing centers, the output file name has a "wetPrf_" prefix and "_nc" suffix. The following sections describe in detail file name convention and file content.

2. File Name Convention

Output file name after the STAR GNSS RO-1DVAR processing is generated using the following template:

FileName = "wetPrf_*FileStamp*_STAR.Vn.n_nc"

Red color marks unchangeable parts of the FileName: "wetPrf" is a type of output, "STAR" is a processing center (NOAA/NESDIS/STAR), "Vn.n" is the software version number, and "_nc" is for the file extension (NetCDF format).

FileStamp is a string with 23 symbols in the form "XXXX.yyyy.doy.hh.mm.gns". Here "XXXX" is a mission identifier, which depends on the missions (see Table 1 for different GNSS receiver satellite missions). Values of "yyyy", "doy", "hh", and "mm" are year, Julian day of the year, hour, and minute of the RO observation, respectively. The "gns" is the GNSS satellite identifier, with the first letter as "G" for GPS, "R" for GLONASS, "E" for Galileo, or "C" for BeiDou, and the rest two are two-digit GNSS satellite number.

Table 1. GNSS receiver satellite missions

XXXX	Meaning
C0nn	COSMIC-1, nn: 01-06, FM1 to FM6
C2En	COSMIC-2, n: 1-6, FM 1 to FM 6
KOM5	KOMPSAT5
MTPn	MetOp, n: A, B, or C
PAZn	PAZ, n: 1
Snnn	Spire, nnn: three-digit satellite ID

GOnn	GeoOptics, nn: two-digit satellite ID

3. Output File Content

3.1 Dimensions

STAR GNSS RO-1DVAR output file has only one dimension variable, named MSL_alt, which is the length (number of levels) for the output profiles.

3.2 Attributes

STAR RO-1DVAR output file attribute variables are presented in Table 2:

Table 2. STAR RO-1DVAR output NetCDF file attribute variables:

Name	**Meaning**
fileStamp	File Stamp: explained in Section 1 of this User Guide
year	Year of the RO observation
month	Month of the RO observation
day	Day of the month of the RO observation
hour	Hour of the RO observation
minute	Minutes of the RO observation
second	Seconds of the RO observation
DOY	Julian day of year of the RO observation
date	Date of the RO observation in format “yyyy-mm-dd_hh:mm:ss.ssss”
atmPrf	Name of the input atmPrf file
fgsUsed	Description of the atmospheric model used as the First Guess in RO-1DVAR
lat	Nominal latitude (degrees North, -90:+90)
lon	Nominal longitude (degrees East, -180:+180)
landmask	“0”=Ocean; ‘1”=Land
Overall_retrieval_quality	Quality flag of the STAR RO-1DVAR processing (“0” means “good”, otherwise “bad”)
H_switch	The altitude (unit=km) where switching from dry retrieval to wet retrieval happens
atmPrf_stdv	Copy of the variable “stdv” from input atmPrf file
atmPrf_snr1avg	Copy of the variable “snr1avg” from input atmPrf file
atmPrf_snr2avg	Copy of the variable “snr2avg” from input atmPrf file
atmPrf_irs	Copy of the variable “irs” from input atmPrf file
atmPrf_balmax	Copy of the variable “balmax” from input atmPrf file
atmPrf_zbalmax	Copy of the variable “zbalmax” from input atmPrf file
atmPrf_freq1	Copy of the variable “freq1” from input atmPrf file
atmPrf_freq2	Copy of the variable “freq2” from input atmPrf file
atmPrf_bad	Copy of the quality flag “bad” from input atmPrf file
bad	Quality flag of the STAR RO-1DVAR processing (“0” means “good”, otherwise “bad”)

version	STAR RO-1DVAR software version number
center	Name of the processing center
NCProperties	NetCDF software version used to make file

3.3 Output Profiles

The collection of output profiles after STAR GNSS RO-1DVAR processing is presented in Table 3. All profiles are one-dimensional arrays of length MSL-alt.

Table 3. STAR GNSS RO-1DVAR output NetCDF file profiles:

Name	Type	Units	Range	Meaning
MSL_alt	float	km	0.0 to 60.0	Mean sea level altitude of perigee point
QC_lev	integer	n/a	0 or 1	Retrieval quality flag by level: 0=bad, 1=good
lat	float	degrees	-90 to +90	Latitude of perigee point
lon	float	degrees	-180 to +180	Longitude of perigee point
Temp	float	Celsius	-200 to 100	Retrieved temperature
Pres	float	mbar	0 to 1200	Retrieved pressure
Vp	float	mbar	0 to 100	Retrieved water vapor partial pressure
sph	float	g/kg	0 to 100	Computed specific humidity
rh	float	%	0 to 100	Computed relative humidity
ref	float	N-units	0 to 500	STAR thinning observed or corrected refractivity
temp_dry	float	Celsius	-200 to +100	Retrieved dry temperature
pres_dry	float	mbar	0 to 1200	Retrieved dry pressure
Temp_1gs	float	Celsius	-200 to +100	Used First Guess temperature
Vp_1gs	float	mbar	0 to 100	Used First Guess Water vapor partial pressure

4. General Description of the Inversion Algorithm

Our team at STAR created an independent 1DVAR inversion algorithm, which is different from UCAR's 1DVAR algorithm. This algorithm converts refractivity profiles into temperature and water vapor profiles. The refractivity (N) in a neutral atmosphere is dependent on pressure (P), temperature (T), and partial pressure of water vapor (P_W), according to Bean and Dutton (1966).

$$N = 77.6\frac{P}{T} + 3.73\times 10^5 \frac{P_W}{T^2} \tag{1}$$

In the troposphere, the refractivity is largely influenced by moisture, while in the stratosphere and upper troposphere, where moisture is negligible, it is mainly determined by temperature. We use the dry hydrostatic equation and the modified Eq. (1) without the second term to solve for dry temperature and dry pressure, which provides a close approximation of the actual temperature.

The inversion of temperature and water vapor from a single variable (N) in the troposphere, where water vapor is present, is a challenging problem. To solve this, we employ the maximum likelihood method proposed by Rodgers (1976) to derive temperature and water vapor from the refractivity at certain altitudes.

$$X_{i+1} = X_0 + (K_i^T E^{-1} K_i + B^{-1})^{-1} \times K_i^T E^{-1} \{(Y_{OBS} - Y(X_i)) + K_i(X_i - X_0)\} \qquad (2)$$

Given the observation of refractivity (Y_{OBS} = N(z_i)) at a height z for iteration i, the optimal estimation of retrieval vector X = (T(z_i), P_W(z_i)) is found through the maximum likelihood inversion in Eq. (2). This involves using the a priori profile for temperature (T_0) and water vapor pressure (P_{W0}), the Jacobian vector (K), the a priori background state covariance matrix (B), and the error covariance matrix (E) that accounts for instrument noise and forward model error. The iteration continues until the difference between observed and simulated refractivity is within 0.1% as specified in Eq. (3).

$$|N_{OBS} - N_i| / N_{OBS} \leq 0.001 \; (i.e., 0.1\,\%) \qquad (3).$$

The initial a priori atmospheric state (X_0 in Eq. (2)) is obtained from the 6-hour forecasting data of NOAA's Global Forecast System (GFS), which is interpolated to the RO locations and time. The 4-dimensional global fields of atmospheric temperature and water vapor can be downloaded from the NOAA National Centers for Environment Information GFS website (website https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs).
The implementations of the STAR 1D var, including the pre-defined a priori background state covariance matrix (B), the error covariance matrix (E), and the validation results, are summarized in Ho et al. (2022).

5. Citation of the STAR 1D Var data product

Ho, S.-p.; Kireev, S.; Shao, X.; Zhou, X.; Jing, X. Processing and Validation of the STAR COSMIC-2 Temperature and Water Vapor Profiles in the Neutral Atmosphere. Remote Sens. **2022**, 14, 5588. https://doi.org/10.3390/ rs14215588.

References

Bean, B.R.; Dutton, E.J. Radio Meteorology. National Bureau of Standards Monogr., No. 92; U.S. Government Printing Office: Washington, DC, USA, 1966; p. 435.

Ho, S.-p.; Kireev, S.; Shao, X.; Zhou, X.; Jing, X. Processing and Validation of the STAR COSMIC-2 Temperature and Water Vapor Profiles in the Neutral Atmosphere. Remote Sens. **2022**, 14, 5588. https://doi.org/10.3390/ rs14215588

Rodgers, C.D. Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. Geophys. Space Phys. **1976**, 14, 609–624.