SnowEx20-21 Time Series UAVSAR L-band Interferometric SAR

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Contents

This document sets out to provide broad overviews and advice on: (1) understanding some concepts being synthetic aperture radar (SAR) (2) finding and using UAVSAR datasets, (3) what are the available UAVSAR data acquisitions in support of the NASA SnowEx campaigns, (4) some context to how and why UAVSAR was part of SnowEx, and (5) provide external references for those interested in delving deeper into UAVSAR, SnowEx, or SAR snow monitoring techniques.

1 What is Synthetic Aperture Radar?

Radar systems actively emit electromagnetic waves in the microwave frequency range (0.1-300 GHz) and measure the returning amplitude and phase of the returning waves. This phase and amplitude information can be parsed to better understand objects' locations, surface, soil, or overlying snow or vegetation characteristics, and atmospheric information, along with many other uses. A challenge of traditional radar arrays is that the spatial resolution was limited by the size of the antenna and impractically large radar antennas would have been necessary for radar measurements from space. This challenge was addressed by the introduction of synthetic aperture radar techniques.

Synthetic aperture radar (SAR) is a radar technique that uses the movement of the imaging platform (ground, air, or space based) to generate a synthetic "antenna" that is much larger than the actual physical antenna. By combining returns from multiple locations along a platform's movement (using the doppler response to determine where the responses were coming from) and integrating the returning amplitudes and phases, images of much higher spatial resolution were possible than with a real aperture radar.

A detailed description of radar and SAR is beyond the scope of this manual but interested readers are directed to the two links and relevant citations given at the bottom of this section.

NASA websites describing SAR:

https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

https://nisar.jpl.nasa.gov/mission/get-to-know-sar/overview/#:~:text=Synthetic%20aperture%20radar%20(SAR)%20refers,of%20NISAR%2C%20orbiting%20in%20space.

Example SAR processor built in python for demonstration:

https://github.com/parosen/Geo-SInC

Relevant publications:

Rosen et al. (2000)
Flores et al. (2019)
Moreira et al. (2013)
Ulaby et al. (1986)

2 What is UAVSAR?

UAVSAR is an airborne platform that operates a L-band SAR instrument. It is operated and processed by the NASA Jet Propulsion Laboratory (JPL). It was designed to simulate SAR imagery from an upcoming NASA-ISRO satellite called NISAR and provide rapid response time for monitoring of natural disasters.

The sensor operates as in quad-polarized mode meaning it transmits and receives waves that have been both polarized in the horizontal (H) and vertical orientation (V). This results in 4 distinct polarization: waves that were transmitted vertically and received vertically (VV), transmitted vertically and received horizontally (VH), transmitted horizontally and received vertically (HV) and transmitted and received horizontally (HH).

A note on the name. While the platform is called "UAV" - SAR it is not actually uncrewed. Instead the UAV naming comes from a "precision real-time GPS and a sensor controlled flight management system" that allows the platform to "fly predefined paths with great precision (to be within a 10 m diameter tube about the desired flight track)." https://airbornescience.nasa.gov/instrument/UAVSAR.

Additional technical specifications are provided below and come from Rosen et al. (2006):

Additional information on the UAVSAR platform can be found at:

Frequency	1.26 GHz
Free air wavelength	0.2379 meters
Antenna Size	0.5 x 1.6 m
Nominal spatial resolution	0.6 m azimuth, 1.6 m range
Bandwidth	80 MHz
Pulse Duration	30 μ seconds
Leads to an azimuth spatial resolution of 0.6 m	
Polarizations	VV, VH, HV, HH
Called Quad Polarization	
Range Swath	16 km
Ground distance covered by a single pulse	
Look angles	25-60°
Transmit Power	2.0 kW
Altitude Range	2000-18000 m
Usually capture at 12.5 km	
Ground speed	100 - 250 m/s
Platform	Gulfstream III

Table 1: UAVSAR System Specifications

Links:
https://airbornescience.nasa.gov/instrument/UAVSAR
https://www.jpl.nasa.gov/missions/uninhabited-aerial-vehicle-synthetic-aperture-radar-uavsar
https://uavsar.jpl.nasa.gov/education/what-is-uavsar.html

Citations relevant to UAVSAR system design are:
Initial system design: Rosen et al. (2006)
Preliminary system review: Hensley et al. (2008)
Polarimetric calibration: Fore et al. (2015)

3 Why was UAVSAR a part of the NASA SnowEx 2020 and 2021 Western U.S Time Series campaigns

The NASA SnowEx campaigns were a: "a multi-year field experiment, which includes extensive surface-based observations to evaluate how to best combine different remote sensing technologies to accurately observe snow throughout the season in various landscapes."(https://snow.nasa.gov/campaigns/snowex, Durand et al. 2019). UAVSAR fights were sponsored by NASA's Terrestrial Hydrology Program (THP) for data collection during the NASA SnowEx 2020 and 2021 Western U.S Time Series Field Campaigns.

One exciting technique to study snow uses the change in radar waves travel times as a result of snow accumulation and UAVSAR was employed during the NASA SnowEx campaigns to study whether the snow retrievals from changes in SAR travel time between UAVSAR acquisitions could be used to retrieve snow depth and snow water equivalent (SWE) changes.

A tutorial walking through UAVSAR SWE retrievals was presented as part of the 2022 SnowEx hackweek: https://snowex-2022.hackweek.io/tutorials/uavsar/1_accessing_imagery.html.

Additional information about the experimental plans is available at:

2020:
https://snow.nasa.gov/campaigns/snowex-2020-time-series-ts-and-intensive-observation-period-iop

2021:
https://snow.nasa.gov/campaigns/snowex-2021-time-series-western-us

3.1 Why did SnowEx fly over these sites and these times?

The sites were selected as part of SnowEx to represent different snow climates, vegetation, and topography types.

The flights were done at approximately 12-day intervals to match the expected repeat interval of the upcoming NISAR satellite. Weather, mechanical issues, and other UAVSAR priorities affected the timings as well.

3.2 Will there be more SnowEx UAVSAR flights in the future?

No future SnowEx UAVSAR collaborations are planned as of 2024-07-19. SnowEx field activities ended Fall 2023.

4 When and where did UAVSAR acquire SAR images for the NASA SnowEx campaigns?

UAVSAR captured imagery for the 2017, 2020 and 2021 NASA SnowEx campaigns (Figure 1). Note that a site in Montana called the Central Agricultural Research Center (CARC) is missing from Figure 1. The sites captured are illustrated in the figure below. Since the UAVSAR imagery is named according to the JPL convention (nearest city) the UAVSAR campaign names differ from the SnowEx site names. The two names and the number of acquisitions (available as of 2024-07-19) in 2020 and 2021 are shown in table 2. Since only Grand Mesa, CO was acquired in 2017 (5 images; 2/06, 2/22, 2/25, 3/08, 3/31) it is not included in table 2. Also note that although the "Boise River Basin" SnowEx site is in Idaho it has the wrong state (CO) in the JPL campaign name.

For those hoping to find and download a specific campaign we suggest either using uavsar_pytools mentioned above or using the JPL UAVSAR data search tool (Figure 2.

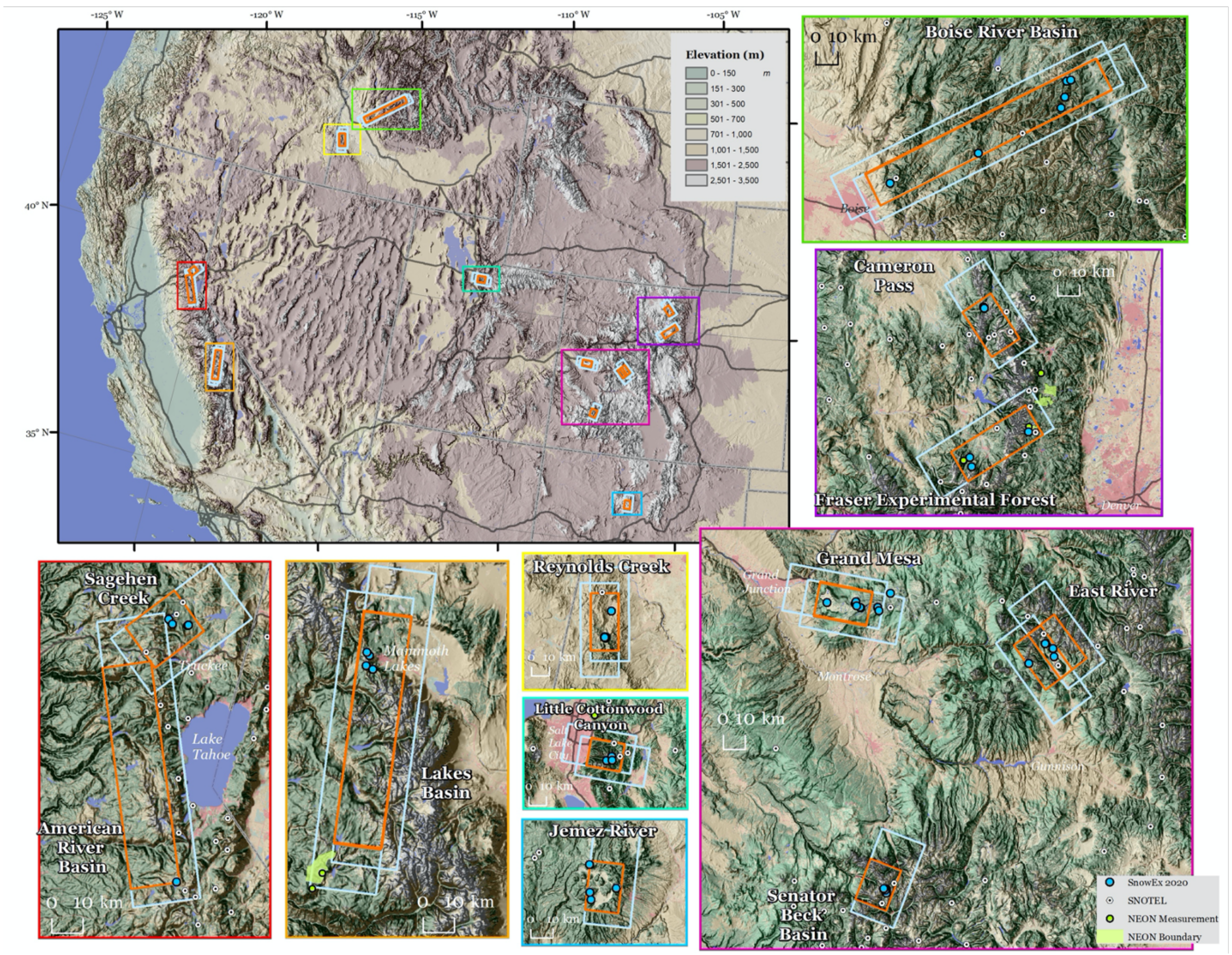


Figure 1: Study sites in the 2020, 2021 SnowEx Campaigns. Note the Central Agrciultural Research Center (CARC) is missing from this figure. Figure credit: Chris Hiemstra

SnowEx Site Name	UAVSAR Campaign Name (abbreviation)	2020 UAVSAR Acquisitions	2021 UAVSAR Acquisitions
Colorado			
Grand Mesa	Grand Mesa, CO (grmesa)	2020-03-12, 2020-02-26, 2020-02-19, 2020-02-12, 2020-02-01	2021-03-22, 2021-03-16, 2021-03-10, 2021-03-03, 2021-02-10, 2021-02-03, 2021-01-27
Senator Beck Basin	Ironton, CO (irnton)	2020-02-12, 2020-02-19, 2020-02-26, 2020-03-12	2021-01-15, 2021-01-21, 2021-01-28, 2021-02-04, 2021-02-11, 2021-02-23, 2021-03-03, 2021-03-10, 2021-03-16, 2021-03-22
East River	Peeler Peak, CO (peeler)	2019-12-20, 2020-02-12, 2020-02-19, 2020-02-26, 2020-03-12	
Fraser Experimental Forest	Fraser, CO (fraser)	2020-02-12, 2020-02-19, 2020-02-26, 2020-03-12	2021-01-15, 2021-01-20, 2021-01-27, 2021-02-03, 2021-02-23, 2021-03-03, 2021-03-10, 2021-03-16, 2021-03-22
Cameron Pass	Rocky Mountains NP, CO (rockmt)	2020-02-12, 2020-02-19, 2020-02-26, 2020-03-12	2021-01-15, 2021-01-20, 2021-01-27, 2021-02-03, 2021-02-23, 2021-03-03, 2021-03-10, 2021-03-16, 2021-03-22
Idaho			
Boise River Basin	Lowman, ID (lowman)	2019-12-20, 2020-01-31, 2020-02-13, 2020-02-21, 2020-03-11	2021-01-15, 2021-01-20, 2021-01-27, 2021-02-03, 2021-02-10, 2021-02-23, 2021-03-03, 2021-03-10, 2021-03-16, 2021-03-22
Reynold Creek	Silver City, ID (silver)	2020-01-31, 2020-02-13, 2020-02-21, 2020-03-11	
Utah			
Little Cottonwood Canyon	Salt Lake City, UT (stlake)	2020-01-31, 2020-02-13, 2020-02-21, 2020-03-12	2021-01-15, 2021-01-21, 2021-01-28, 2021-02-03, 2021-02-10, 2021-02-23, 2021-03-03, 2021-03-10, 2021-03-16, 2021-03-22
Montana			
Central Agricultural Research Center (CARC)	Utica, MT (uticam)		2021-01-15, 2021-01-20, 2021-02-23
New Mexico			
Jemez River	Los Alamos, NM (alamos)	2020-02-12, 2020-02-19, 2020-02-26	
California			
American River Basin	Eldorado National Forest, CA (dorado)	2020-01-31, 2020-02-12, 2020-02-19, 2020-02-26, 2020-03-11	
Sagehen Creek	Donner Memorial State Park, CA (donner)	2019-12-20, 2020-01-31, 2020-02-12, 2020-02-19, 2020-02-26, 2020-03-11	
Lakes Basin	Sierra National Forest, CA (sierra)	2020-01-31, 2020-02-12, 2020-02-19, 2020-02-26, 2020-03-11	

Table 2: UAVSAR Campaign Acquisitions for SnowEx Sites

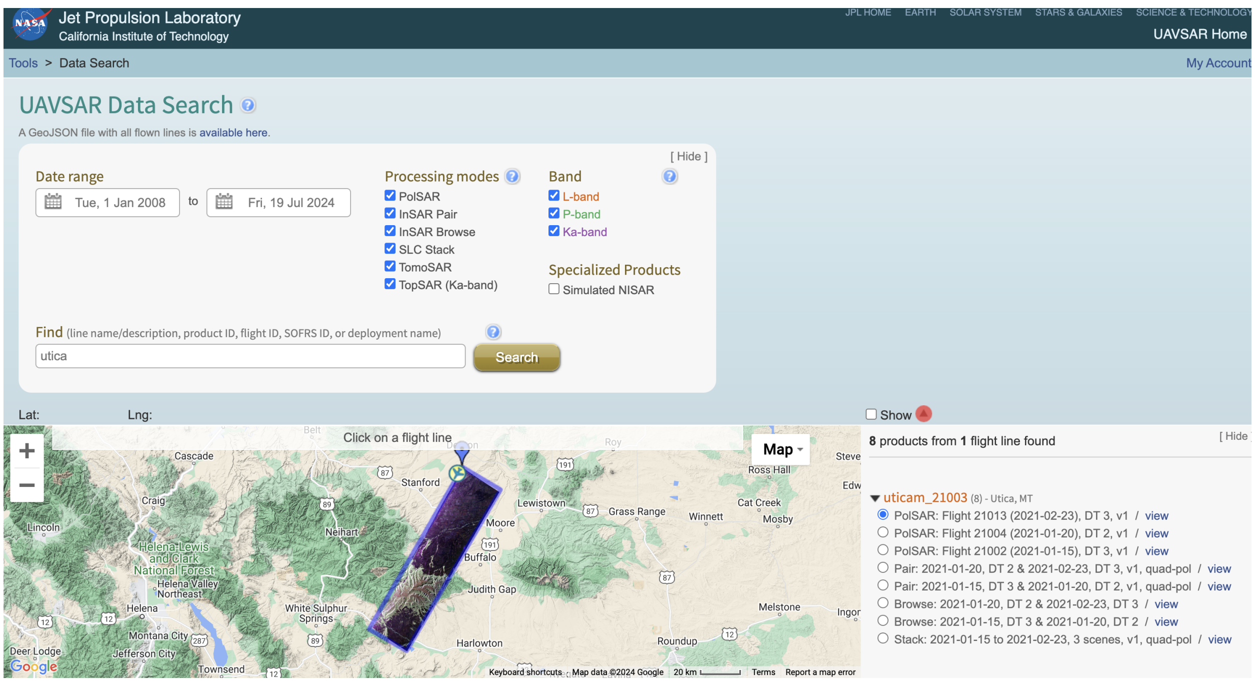


Figure 2: Screen capture of the JPL UAVSAR datasearch being used to find UAVSAR images from the Utica, MT SnowEx site from Table 2.

5 What are the available UAVSAR data products?

Data products are available from two sources: the Jet Propulsion Laboratory UAVSAR data search (https://uavsar.jpl.nasa.gov/cgi-bin/data.pl) or the Alaska Satellite Facility's Data Search Vertex (https://search.asf.alaska.edu/#/).

There are three general classes of UAVSAR data products:

- Repeat Pass Interferograms (RPI or InSAR) - these files contain the wrapped, unwrapped phase changes, and resulting coherence rasters between two UAVSAR image acquisitions. These are the primary scientific focus of the NASA SnowEx campaign and will be explored in detail below. https://uavsar.jpl.nasa.gov/science/documents/rpi-format.html
- Polarimetric SAR (PolSAR) - these are the power (linear not dB) of cross-products between the different polarizations. For example the S_HHS_HV is the cross product of the phase of HH multiplied by the complex conjugate of the phase of HV. The six combinations of cross products are available (HHHV, HHVV, HVVV, HHHH, HVHV, VVVV) with an assumption that the two cross product HV and VH contain the identical information. These cross products can then be used to generate polarimetric decomposition that describe the scattering characteristics of ground targets. Polarimetric decompositions are beyond the scope of this document but users interested in decompositions are directed to:
  https://uavsar.jpl.nasa.gov/science/documents/polsar-format.html
  https://appliedsciences.nasa.gov/sites/default/files/Session3-SAR-English.pdf
  https://dges.carleton.ca/courses/IntroSAR/Winter2019/SECTION%203%20-%20Carleton%20SAR%20Training%20-%20SAR%20Polarimetry%20%20-%20Final.pdf
- Single Look Complex (SLC) Stacks - These are coregistered stacks of SLC images for different campaigns. These can be useful for users interested in processing their own interferograms or other more advanced time series techniques. Single-look means these images have not been spatially averaged through a process called multi-looking, complex means these have both a real and an imaginary value for each pixel.

Some of the other ancillary data files include: height files (.hgt) used in the processing, incidence angle files (.inc), look vectors showing the vector between a ground point and the zero-doppler point for UAVSAR in the scene (.lkv), files containing the latitudes, longitudes, and heights for each pixel of the radar scene (.llh), and slope files (.slope).

These files will generally have one more extension (.grd). This represents that this file has been "ground projected" or orthorectified to match a DEM. When SAR images are first processed they are in slant range which represents the distance from the platform to varying ground locations either along the direction of travel (azimuth) or in the direction the sensor is transmitting and receiving (range). These slant range files need additional processing so the pixels correspond to latitudes and longitudes on the ground surface and will not have this .grd extension. Generally, new users of UAVSAR will want to use ground projected files.

5.1 Repeat Pass Interferograms naming convention

UAVSAR repeat pass interferometry uses two images of the same place but separated in time. Phase changes between the two acquisitions are calculated, creating an interferogram. This calculation involves multiplying the first sar image by the complex conjugate of the second sar image. These phase changes are due to either the wave traveling a longer distance (ground movement or refraction) or change wave speeds (atmospheric water vapor and snow).

We will now explore the data files and naming conventions of the UAVSAR repeat pass interferograms. First, we will walk through an example file name to demonstrate the general naming conventions. Note that this information is expanded from: https://uavsar.jpl.nasa.gov/science/documents/rpi-format.html. The file names will be similar for all files in a single InSAR directory until the final polarization, version, file type (HH_01.cor.grd in our example below). Also since these repeat pass interferograms are the difference between two UAVSAR acquisitions we will highlight which of the naming sections is the same for both acquisitions and which is unique to flight 1 or two. We begin by splitting the underscores to parse the individual meanings.

lowman_23205_21019-018_21021-006_0006d_s01_L090HH_01.cor.grd

lowman: This is the UAVSAR designated campaign name. Usually it will correspond to a city or town near the survey location.

23205: This corresponds to both flight 1 and 2 of this pair of SAR images. this is split into the first three characters (232) which represent the flight heading (the plane flew with a heading of 232°) then the last two characters (05) are an numeric counter assigned to this campaign and flight direction.

21019: This corresponds to flight 1 of this pair. this is again split with the first two characters (21) representing the flight year (2021) and the following three characters (019) representing the flight number for that year (this is the 19th time this heading and survey location was imaged).

-018: this represents which flight line of the flight this acquisition was starting from zero. UAVSAR will often acquire imagery for multiple campaigns or sites on a single flight. So this was the 19th flight observed on the particular flight of UAVSAR.

21021: This corresponds to flight 2 of this pair. It again shows the year (21 i.e. 2021) and which acquisition of this flight line this was this year (21st acquisition of the "lowman" line in 2021).

-006: This corresponds to flight 2 of this pair. This was the 7th (since we start from zero) acquisition of this flight of UAVSAR.

0006d: 6 days separated flight 1 and flight 2.

s01: three character id. Usually s01.

L090HH: L represents L-band. UAVSAR can also operate at different frequencies. 090 represents that the sensors was transmitted and receiving perpendicular to the flight direction (as opposed to pointing slightly forwards or backwards), and for this particular image the polarization is HH. The energy was transmitted horizontally and received on the horizontally polarized antenna.

01: This is the version number if multiple rounds of processing were done.

.cor: represents the file type. In this case coherence. The different inteferogram file types will be outlined more below.

.grd: ground projected. This was discussed above but represents that the radar phase is processed to relate to specific latitudes and longitudes on the ground.

As mentioned above most of these will be the same for a single interferogram pair except for the polarization (HH in this case) which can be any combination of HH, HV, VH, VV and file type (.cor in this case) which we will now discuss the file types available for the interferogram file type. Again some of this information comes from: `https://uavsar.jpl.nasa.gov/science/documents/rpi-format.html`.

5.2 Interferogram File Types

The file types available with each interferogram are shown below in a table. Note that the extensions shown will often have a .grd after them for ground projected files.

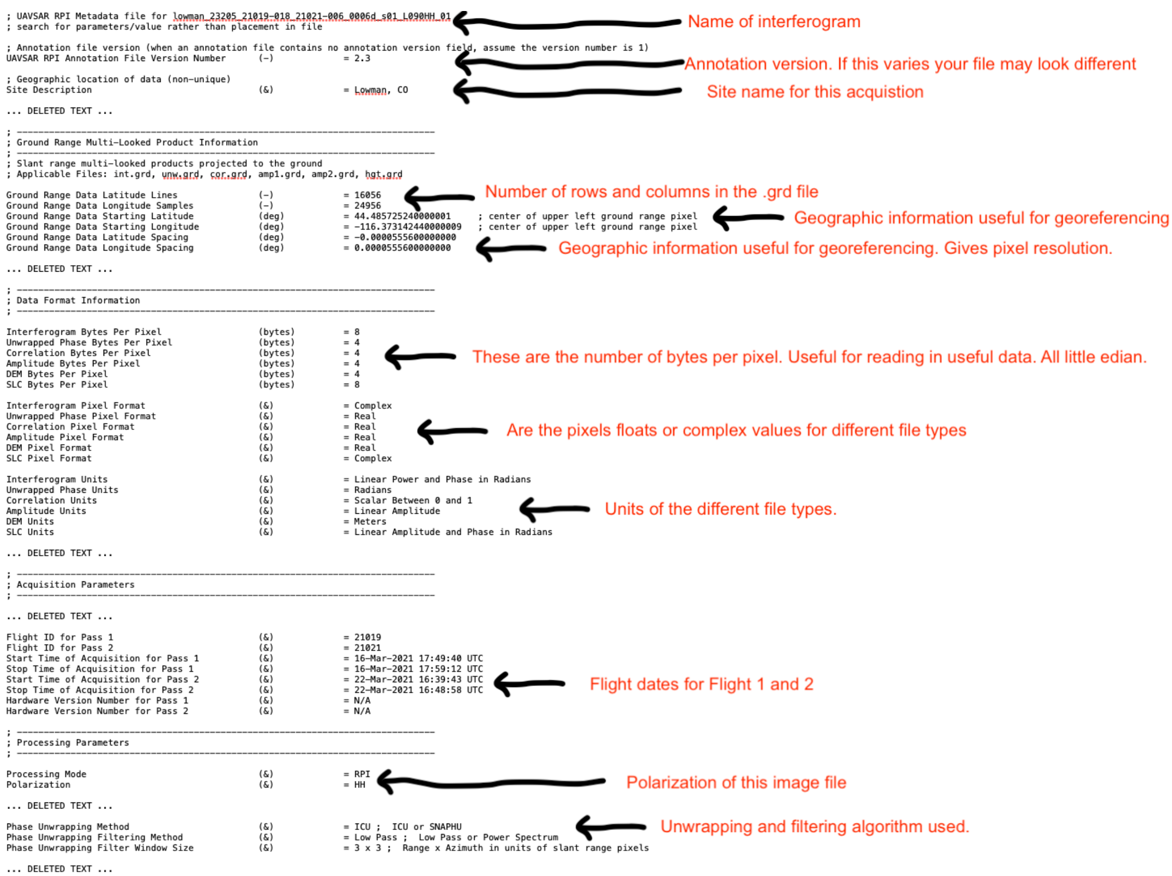
File Type	Extension	Description
Annotation	.ann	Provides important information about the images and flight including: flight dates for flight 1 and 2, number of rows and columns, approximate geographic coordinates, byte number and type, degree of multi-looking, units, headings, processing parameters.
Wrapped interferogram	.int	This represents the interferogram. It is the cross product of SAR image 1 with the complex conjugate of SAR image 2.
Unwrapped phase	.unw	Unwrapped phases from the .int SAR file showing the phase changes between flight 1 and 2. The exact unwrapping method (ICU or SNAPHU) is specified in the .ann file.
Coherence	.cor	These are the coherence files showing the similarity of phase changes in a spatial neighborhood. A measure of the noise for the phase change.
DEM	.hgt	The DEM used in the processing.
Amplitude 1	.amp1	Calibrated multi-looked amplitude of SAR image 1. Not included in all interferogram directories.
Amplitude 2	.amp2	Calibrated multi-looked amplitude of SAR image 2. Not included in all interferogram directories.

Table 3: Description of interferogram files

5.3 Annotation file description

The annotation (.ann) file contains all the necessary information to read and parse the data files it relates to. We now present an annotated and shortened .ann file. We have removed large sections of text intended for advanced SAR users to highlight the critical components for a new user of UAVSAR.

6 What are useful software and tools for working with UAVSAR dataset?



```
; UAVSAR RPI Metadata file for lowman_23205_21019-018_21021-006_0006d_s01_L090HH_01
; search for parameters/value rather than placement in file

; Annotation file version (when an annotation file contains no annotation version field, assume the version number is 1)
UAVSAR RPI Annotation File Version Number      (-)              = 2.3

; Geographic location of data (non-unique)
Site Description                               (&)              = Lowman, CO

... DELETED TEXT ...

; ------------------------------------------------------------------------------
; Ground Range Multi-Looked Product Information
; ------------------------------------------------------------------------------
; Slant range multi-looked products projected to the ground
; Applicable Files: int.grd, unw.grd, cor.grd, amp1.grd, amp2.grd, hgt.grd

Ground Range Data Latitude Lines               (-)              = 16056
Ground Range Data Longitude Samples            (-)              = 24956
Ground Range Data Starting Latitude            (deg)            = 44.485725240000001    ; center of upper left ground range pixel
Ground Range Data Starting Longitude           (deg)            = -116.373142440000009  ; center of upper left ground range pixel
Ground Range Data Latitude Spacing             (deg)            = -0.0000555600000000
Ground Range Data Longitude Spacing            (deg)            = 0.0000555600000000

... DELETED TEXT ...

; ------------------------------------------------------------------------------
; Data Format Information
; ------------------------------------------------------------------------------

Interferogram Bytes Per Pixel                  (bytes)          = 8
Unwrapped Phase Bytes Per Pixel                (bytes)          = 4
Correlation Bytes Per Pixel                    (bytes)          = 4
Amplitude Bytes Per Pixel                      (bytes)          = 4
DEM Bytes Per Pixel                            (bytes)          = 4
SLC Bytes Per Pixel                            (bytes)          = 8

Interferogram Pixel Format                     (&)              = Complex
Unwrapped Phase Pixel Format                   (&)              = Real
Correlation Pixel Format                       (&)              = Real
Amplitude Pixel Format                         (&)              = Real
DEM Pixel Format                               (&)              = Real
SLC Pixel Format                               (&)              = Complex

Interferogram Units                            (&)              = Linear Power and Phase in Radians
Unwrapped Phase Units                          (&)              = Radians
Correlation Units                              (&)              = Scalar Between 0 and 1
Amplitude Units                                (&)              = Linear Amplitude
DEM Units                                      (&)              = Meters
SLC Units                                      (&)              = Linear Amplitude and Phase in Radians

... DELETED TEXT ...

; ------------------------------------------------------------------------------
; Acquisition Parameters
; ------------------------------------------------------------------------------

... DELETED TEXT ...

Flight ID for Pass 1                           (&)              = 21019
Flight ID for Pass 2                           (&)              = 21021
Start Time of Acquisition for Pass 1           (&)              = 16-Mar-2021 17:49:40 UTC
Stop Time of Acquisition for Pass 1            (&)              = 16-Mar-2021 17:59:12 UTC
Start Time of Acquisition for Pass 2           (&)              = 22-Mar-2021 16:39:43 UTC
Stop Time of Acquisition for Pass 2            (&)              = 22-Mar-2021 16:48:58 UTC
Hardware Version Number for Pass 1             (&)              = N/A
Hardware Version Number for Pass 2             (&)              = N/A

; ------------------------------------------------------------------------------
; Processing Parameters
; ------------------------------------------------------------------------------

Processing Mode                                (&)              = RPI
Polarization                                   (&)              = HH

... DELETED TEXT ...

Phase Unwrapping Method                        (&)              = ICU ;  ICU or SNAPHU
Phase Unwrapping Filtering Method              (&)              = Low Pass ;  Low Pass or Power Spectrum
Phase Unwrapping Filter Window Size            (&)              = 3 x 3 ;  Range x Azimuth in units of slant range pixels

... DELETED TEXT ...
```


Figure 3: Annotated .ann file showing critical components of the file for new users.

For working with UAVSAR we recommend using uavsar_pytools (Hoppinen et al., 2022). An open-source python software package for searching, downloading, and processing the binary UAVSAR data files into GIS-ready geoTIFFs. This software was developed by the SnowEx community to better work with UAVSAR datasets. It also contains functions for UAVSAR polarimetric decompositions, georeferencing SLC stacks, and SWE and snow depth retrievals from UAVSAR phase.

The url is available at: `https://github.com/SnowEx/uavsar_pytools` along with a ReadMe for installation (pip installable) and usage. A selection of the code (Figure 4) for downloading all images of a SnowEx campaign (Table 2) is presented below to show some basic usage. There are also several example notebooks available in the GitHub repository.

```python
from uavsar_pytools import UavsarCollection

## Collection name from the campaign list
col_name = 'Grand Mesa, CO'

## Working directory to save files into
work_d = '~/Documents/collection_ex/'

## Optional dates to check between
dates = ('2019-11-01','2020-04-01')

collection = UavsarCollection(collection = col_name, work_dir = work_d, dates = dates)

# Optional keywords: to keep binary files use `clean = False`, to download incidence angles
# with each image use `inc = True`, for only certain pols use `pols = ['VV','HV']`.
# See docstring of class for full list.

collection.collection_to_tiffs()
```

Figure 4: Example selection of code showing the process to download all UAVSAR images from a specific UAVSAR collection. See table 2 for all campaign names.

7 How do I cite UAVSAR data when I use it?

From the JPL website: "When publishing or presenting UAVSAR data, we request the following acknowledgement: UAVSAR data courtesy NASA/JPL-Caltech. For more information regarding JPL's image use policy, please refer to this document: https://www.jpl.nasa.gov/imagepolicy/"

If using the SnowEx UAVSAR imagery please acknowledge SnowEx and consider citing the experimental plans given below:

2017:
https://snow.nasa.gov/campaigns/snowex-2017-intensive-observation-period-iop

2020:
https://snow.nasa.gov/campaigns/snowex-2020-time-series-ts-and-intensive-observation-period-iop
https://nsidc.org/sites/default/files/documents/technical-reference/nasa_snowex_experiment_plan_2020_draft.pdf

2021:
https://snow.nasa.gov/campaigns/snowex-2021-time-series-western-us

8 Recent publications using UAVSAR and SnowEx

A description of the retrieval technique from UAVSAR interferograms is beyond the scope of this document but interested parties are directed to the following list of recent publications describing the SWE retrieval techniques and using UAVSAR and SnowEx datasets to retrieve snow depth and SWE:

Study	SnowEx Site	Title
Marshall et al. (2021)	Grand Mesa, CO	L-Band InSAR Depth Retrieval During the NASA SnowEx 2020 Campaign: Grand Mesa, Colorado
Tarricone et al. (2023)	Jemez River, NM	Estimating snow accumulation and ablation with L-band interferometric synthetic aperture radar (InSAR)
Palomaki and Sproles (2023)	Central Agricultural Research Center, MT	Assessment of L-band InSAR snow estimation techniques over a shallow, heterogeneous prairie snowpack
Hoppinen et al. (2023)	Boise River Basin, ID	Snow water equivalent retrieval over Idaho – Part 2: Using L-band UAVSAR repeat-pass interferometry
Bonnell et al. (2024)	Cameron Pass, CO	Evaluating L-band InSAR Snow Water Equivalent Retrievals with Repeat Ground-Penetrating Radar and Terrestrial Lidar Surveys in Northern Colorado

Table 4: Studies on UAVSAR InSAR Snow Estimation at NASA SnowEx Sites.

9 References

References

R. Bonnell, D. McGrath, J. Tarricone, H.-P. Marshall, E. Bump, C. Duncan, S. Kampf, Y. Lou, A. Olsen-Mikitowicz, M. Sears, K. Williams, L. Zeller, and Y. Zheng. Evaluating L-band InSAR Snow Water Equivalent Retrievals with Repeat Ground-Penetrating Radar and Terrestrial Lidar Surveys in Northern Colorado. *EGUsphere*, 2024:1–33, 2024. doi: 10.5194/egusphere-2024-236.

A. Flores, K. Herndon, R. Thapa, and E. Cherrington. *The SAR Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation*. 04 2019. doi: 10.25966/nr2c-s697.

A. G. Fore, B. D. Chapman, B. P. Hawkins, S. Hensley, C. E. Jones, T. R. Michel, and R. J. Muellerschoen. UAVSAR Polarimetric Calibration. *IEEE Transactions on Geoscience and Remote Sensing*, 53(6):3481–3491, 2015. ISSN 0196-2892. doi: 10.1109/tgrs.2014.2377637.

S. Hensley, K. Wheeler, G. Sadowy, C. Jones, S. Shaffer, H. Zebker, T. Miller, B. Heavey, E. Chuang, R. Chao, K. Vines, K. Nishimoto, J. Prater, B. Carrico, N. Chamberlain, J. Shimada, M. Simard, B. Chapman, R. Muellerschoen, C. Le, T. Michel, G. Hamilton, D. Robison, G. Neumann, R. Meyer, P. Smith, J. Granger, P. Rosen, D. Flower, and R. Smith. THE UAVSAR INSTRUMENT: DESCRIPTION AND FIRST RESULTS. *2008 IEEE Radar Conference*, pages 1–6, 2008. doi: 10.1109/radar.2008.4720722.

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