Talking to a spaceborne RADAR: signal processing Sentinel1 satellites data

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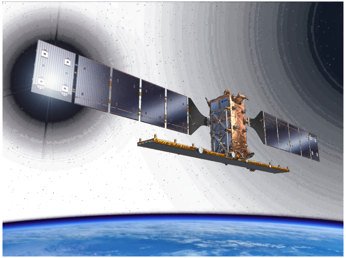


Image from `www.esa.int/`

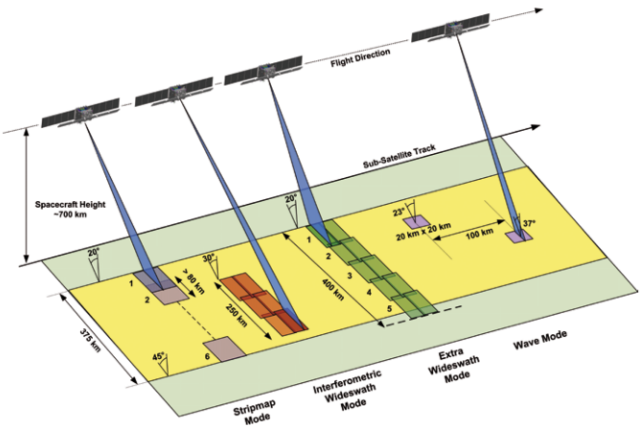
slides at `jmfriedt.free.fr`

Sequel to J.M. Friedt & W. Feng, *Software defined radio based Synthetic Aperture noise and OFDM (Wi-Fi) RADAR mapping*, GRCON2020 at `https://www.youtube.com/watch?v=ad_B4Vil6aw` and `https://pubs.gnuradio.org/index.php/grcon/article/view/71`

January 12, 2021

Spaceborne Synthetic Aperture RADAR

Figure 5.1. Sentinel-1 operational modes.



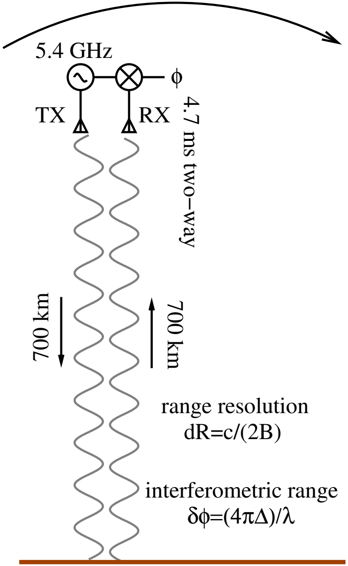
- RADAR: all-weather, day & night observation (active illumination)
- C-band: frequency 5404 ± 50 MHz ($\lambda \simeq 5.6$ cm)
- 700 km altitude, 98.6 minute orbit, polar orbiting/Sun synchronous
- 12-day repetition for each satellite (Sentinel 1A, Sentinel 1B)
- Radiofrequency: access to the *phase* of the returned signal (+polarization)
- Freely available datasets from ESA's `https://scihub.copernicus.eu/dhus`
- Free, opensource processing toolbox SNAP (v8.0) at `http://step.esa.int/main/download/snap-download/` (binary) or (source code) `https://github.com/senbox-org`.

"Sentinel Data Policy: [...] anyone can access acquired Sentinel data; in particular, no distinction is made between public, commercial and scientific uses, or between European or non-European users [...] It is expected that this open and free access to the data (for any purpose, within or outside Europe), will maximise the beneficial use of data for the widest range of applications. It will strengthen EO markets in Europe, in particular the downstream sector, with a view to promoting growth and job creation." (p.67)

From ESA's *Sentinel-1 – ESA's Radar Observatory Mission for GMES Operational Services*, SP-1322/1 (March 2012) at `https://sentinel.esa.int/documents/247904/349449/S1_SP-1322_1.pdf` (p.20)

Basics [1]

- Chirped emission: range compression
- Moving RADAR source along satellite orbit: azimuth compression
- Pixel size: 5 m×20 m
- Phase measurement: interferometry for sub-wavelength displacement analysis
- Orbit designed to repeat observation geometry every 12 days: InSAR (Interferometric Synthetic Aperture RADAR) processing
- Repeated pass: topography variation Δ observed as phase shift $\delta\phi$ with resolution $\ll \lambda$ but with integer $\lambda/2$ ambiguity, $\forall$ topography

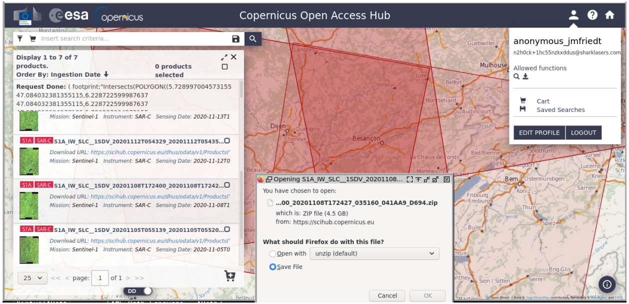


[1] J.A. Johannessen & F. Collard, *SAR Instrument Principles and Processing* (2012) at `https://earth.esa.int/eogateway/documents/20142/0/01_Wednesday_OCT2013_SAR_principles.pdf`

Datasets

Register with ESA's Copernicus web site (can be anonymous – works with Tor) and select the area of interest, period, platform (Sentinel-1 {A, B}) and IW (Interferometric Wide swath) SLC (Single Look, Complex) for InSAR processing

S1A_IW_SLC__1SDV_20201129T055138_2020112
S1A_IW_SLC__1SDV_20201125T173206_2020112
S1A_IW_SLC__1SDV_20201124T054329_2020112
S1A_IW_SLC__1SDV_20201120T172400_2020112
S1A_IW_SLC__1SDV_20201117T055139_2020111
S1A_IW_SLC__1SDV_20201113T173206_2020111
S1A_IW_SLC__1SDV_20201112T054329_2020111
S1A_IW_SLC__1SDV_20201108T172400_2020110
S1A_IW_SLC__1SDV_20201105T055139_2020110
S1A_IW_SLC__1SDV_20201101T173206_2020110



- Each satellite flies over Besançon every 3 or 4 days (red) [2].
- … *but* only similar orbital paths can be compared for interferometric analysis (05513x orange, 17320x blue or 17240x green)
- observation path prediction provided as KML files at [3]

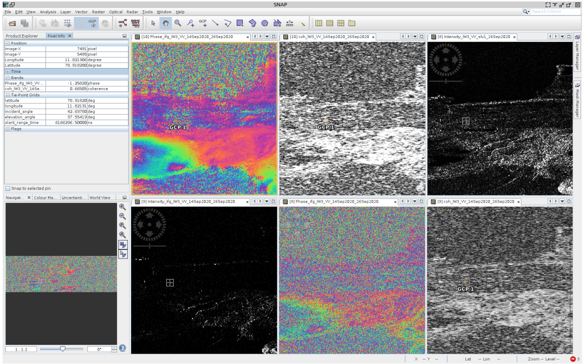
[2]file name is described at https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar/products-algorithms/level-1-product-formatting

[3]sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/observation-scenario/acquisition-segments

SNAP processing software (GUI)

Excellent tutorial at [4] on the *SeNtinel Application Platform*

1. only keep the data segment (burst) with the useful area: *split*
2. apply precise orbital parameters to known where the satellite was located during acquisition (might have to wait up to 20 days): *orbit*,
3. remove data acquisition artifacts: *deburst*
4. geographical projection – selecting the right UTM zone: *Terrain Correction*



We export the output product (found in the .data directory) to GeoTIFF:

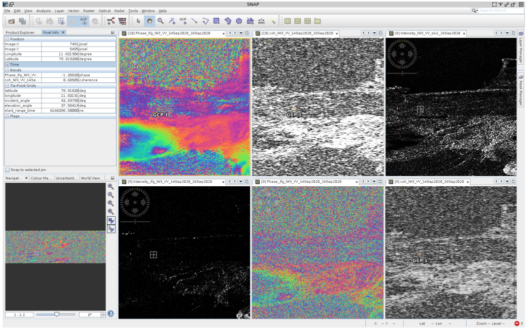
```
gdal_translate -of GTiff ./target_final.data/Int*VV*.img final_intensity.tif
```

[4] *Sentinel-1 Toolbox – TOPS Interferometry Tutorial* (Jan. 2020) at http://step.esa.int/docs/tutorials/S1TBX%20TOPSAR%20Interferometry%20with%20Sentinel-1%20Tutorial_v2.pdf

SNAP processing software (GUI)

Excellent tutorial at [4] on the *SeNtinel Application Platform*

1. only keep the data segment (burst) with the useful area: *split*
2. apply precise orbital parameters to known where the satellite was located during acquisition (might have to wait up to 20 days): *orbit*,
3. for interferometry, co-register a slave and master dataset: *back-geocoding*
4. improve co-registration with *enhanced spectral diversity*
5. complex interferogram calculation: *interferogram*
6. remove data acquisition artifacts: *deburst*
7. remove topographical phase: *topographical*
8. spatial averaging: *multilook*
9. Fourier domain phase filtering: *Goldstein filtering*
10. geographical projection – selecting the right UTM zone: *Terrain Correction*



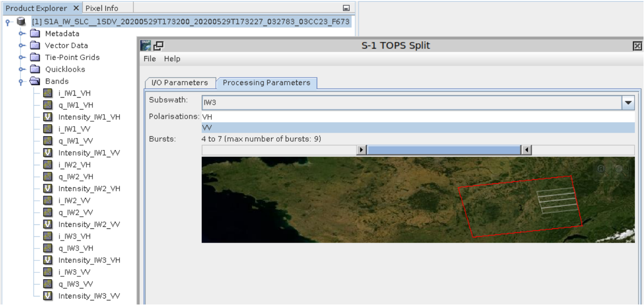
- Only complex (I, Q) datasets are stored, resulting quantities (phase, mag) are computed on the fly.
- `.img` files can be read with QGis

[4] *Sentinel-1 Toolbox – TOPS Interferometry Tutorial* (Jan. 2020) at http://step.esa.int/docs/tutorials/S1TBX%20TOPSAR%20Interferometry%20with%20Sentinel-1%20Tutorial_v2.pdf

gpt processing software (CLI)

Command line tool [5] for accessing the library functions

- Each dataset is dependent on the successful completion of the previous task: `Makefile`
- Many random errors about Java VM heap allocation and communication between threads $\Rightarrow$ reduce parallelization and resource consumption: `-c 2048M -q 2` (Panasonic CF-19 quad-core with 12 GB RAM)
- DEM tiles stored in `~/.snap/auxdata/dem/`
- for custom DEM, no-value is encoded as $-\infty$ leading to processing failure. Make sure a no-value is defined




```
gdal_calc.py -A DEM.tif --calc="A" --outfile=result.tif --NoDataValue=0
```

and inform gpt: `-PexternalDEMNoDataValue=0.0`

$\Rightarrow$ automate processing + reduce risk of error (identifying burst still requires the GUI $\uparrow$)

[5] `http://step.esa.int/docs/tutorials/SNAP_CommandLine_Tutorial.pdf`

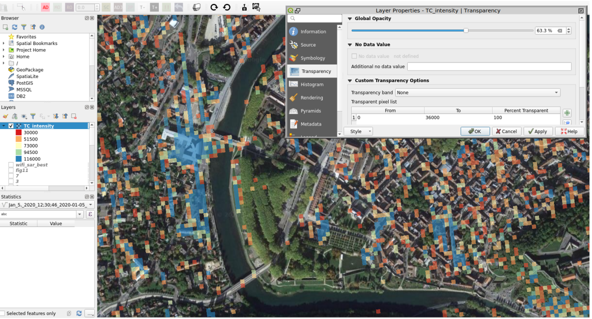
```
GPT=$(HOME)/snap/bin/gpt
FILENAME1=S1A_IW_SLC__1SDV_20190615T054201_20190615T054228_027686_032005_E4D9.zip
FILENAME2=S1A_IW_SLC__1SDV_20190627T054202_20190627T054229_027861_03253C_9240.zip
all: target_final.dim

target_split1.dim: $(FILENAME1)                        # Split
	$(GPT) TOPSAR-Split -Ssource=$(FILENAME1) -PfirstBurstIndex=6 -PlastBurstIndex=9 -Psubswath=IW3 -t target_split1
target_split2.dim: $(FILENAME2)
	$(GPT) TOPSAR-Split -Ssource=$(FILENAME2) -PfirstBurstIndex=6 -PlastBurstIndex=9 -Psubswath=IW3 -t target_split2

target_orb1.dim: target_split1.dim                     # Orbital Params
	$(GPT) Apply-Orbit-File -Ssource=target_split1.dim -t target_orb1
target_orb2.dim: target_split2.dim
	$(GPT) Apply-Orbit-File -Ssource=target_split2.dim -t target_orb2

target_stack.dim: target_orb1.dim target_orb2.dim   # Back Geocoding
	$(GPT) Back-Geocoding -SsourceProducts=target_orb1.dim target_orb2.dim -PdemName="SRTM 3Sec" -t target_stack.dim  -c 8192M -q 8

target_esd.dim: target_stack.dim                       # Enhanced Spectral Diversity: output is target.dim and target.data
	$(GPT) Enhanced-Spectral-Diversity -Ssource=target_stack.dim -t target_esd.dim -c 2048M -q 2

target_interf.dim: target_esd.dim                      # Interferometry
	$(GPT) Interferogram -SsourceProduct=target_esd.dim -t target_interf.dim -PsubtractFlatEarthPhase=true
#  -PdemName="External DEM" -PexternalDEMFile="DEM.tif" -PexternalDEMNoDataValue=0.0

target_deburst.dim: target_interf.dim                  # Deburst
	$(GPT) TOPSAR-Deburst -SsourceProduct=target_interf.dim -t target_deburst.dim -c 2048M -q 2

target_topo.dim: target_deburst.dim                    # Topographic phase removal
	$(GPT) TopoPhaseRemoval -SsourceProduct=target_deburst.dim -PdemName="SRTM 3Sec" -t target_topo.dim

target_ml.dim: target_topo.dim                         # Multilook
	$(GPT) Multilook -SsourceProduct=target_topo.dim -t target_ml.dim

target_gold.dim: target_ml.dim                         # Goldstein Phase Filtering
	$(GPT) GoldsteinPhaseFiltering -SsourceProduct=target_ml.dim -t target_gold.dim

target_final.dim: target_gold.dim                      # Range Doppler Terrain: cf qgis for map projection
	$(eval list1=‘ls target_gold.data/q*img | cut -d\/  -f2 | sed ’s/\.img//g’ | sed ’s/q/Phase/g’ | tr ’\n’ ’,’‘)
	$(eval list2=‘ls target_gold.data/q*img | cut -d\/  -f2 | sed ’s/\.img//g’ | sed ’s/q/Intensity/g’ | tr ’\n’ ’,’ | sed ’s/,/_db/g’‘)
	$(eval list3=‘ls target_gold.data/coh*img | cut -d\/  -f2 | sed ’s/\.img//g’‘)
	$(GPT) Terrain-Correction -SsourceProduct=target_gold.dim -PdemName="SRTM 3Sec" -PmapProjection="EPSG:32632" -PsaveSelectedSourceBand=true \
-PsourceBands="$(list1)$(list2),$(list3)" -t target_final.dim # -PdemName=GETASSE30 -PoutputComplex=true
```

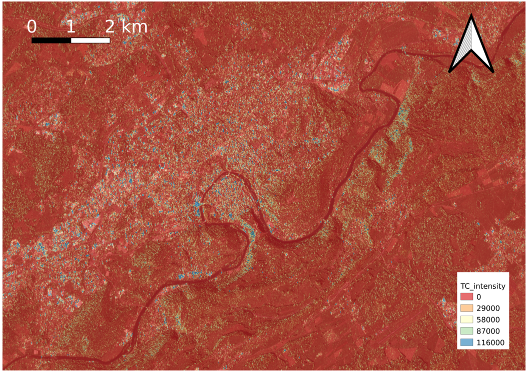
Georeferenced datasets

Conclusion of Makefile:

```
gdal_translate -of GTiff ./target_final.data/Phase*VV*.img final_phase.tif
gdal_translate -of GTiff ./target_final.data/coh*.img final_coh.tif
gdal_translate -of GTiff ./target_final.data/Int*.img final_intensity.tif
```

GeoTIFF files ready to be inserted in QGis

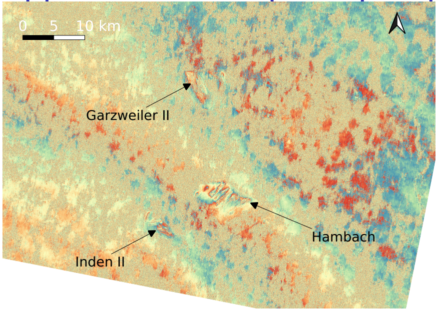


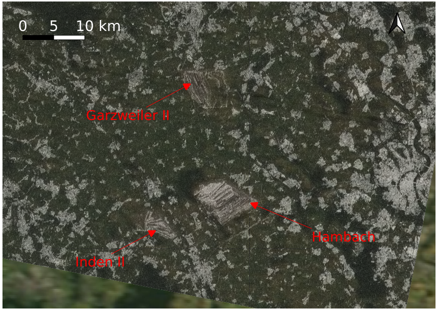


Reflected intensity emphasizing permanent scatterers as modern-shaped buildings
`S1A_IW_SLC__1SDV_20200821T173205_20200821T173232_034008_03F26D_1274_split_Orb_deb.dim` indicates that

<PRODUCT_SCENE_RASTER_START_TIME>21-AUG-2020 17:32:10.661383</PRODUCT_SCENE_RASTER_START_TIME>
<PRODUCT_SCENE_RASTER_STOP_TIME>21-AUG-2020 17:32:19.288552</PRODUCT_SCENE_RASTER_STOP_TIME>

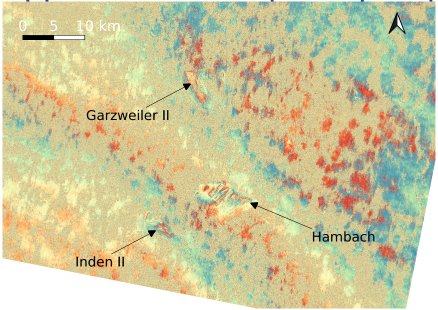
Application example: open-pit coal mining in Germany

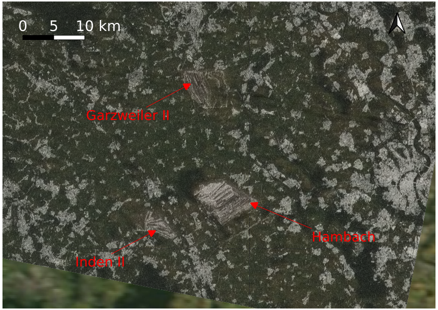


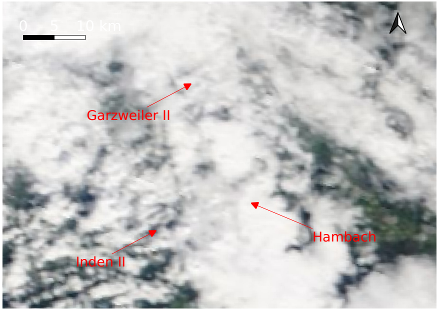


↑ Above: MODIS image collected on the master image date (no cloud cover)
↖ Top-left: interferogram phase (unwraps to displacement with $\varphi/(2\pi) \times 2.8$ cm due to the two-way trip of the wave)
← Bottom-left: correlation intensity, strongest in urban areas

Application example: open-pit coal mining in Germany



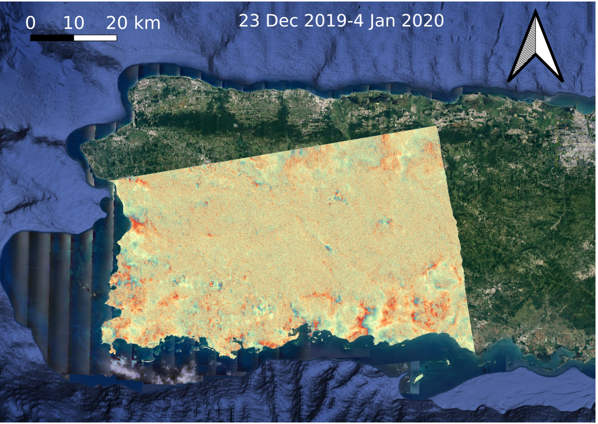


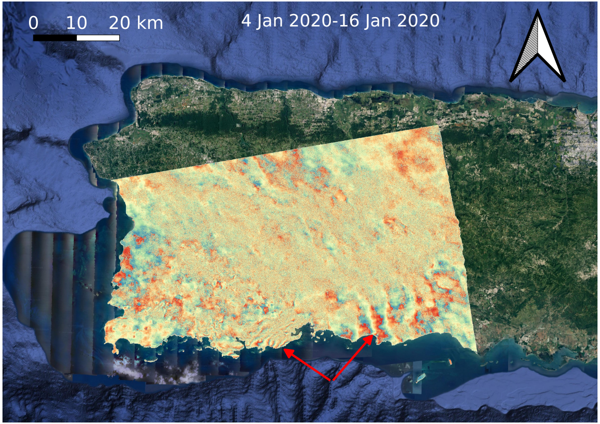


↑ Above: MODIS image collected on the slave image date (heavy cloud cover)
↖ Top-left: interferogram phase (unwraps to displacement with $\varphi/(2\pi) \times 2.8$ cm due to the two-way trip of the wave)
← Bottom-left: correlation intensity, strongest in urban areas

Application example: earthquake

Reference analysis [6] featuring the Jan. 7, 2020 earthquake in Puerto Rico



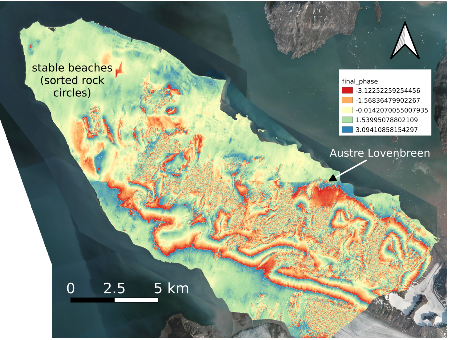


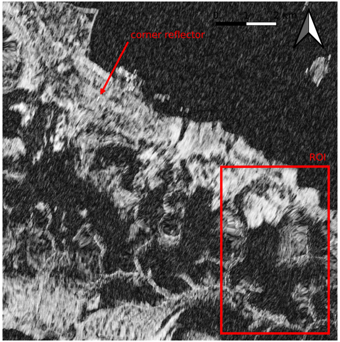
Before After

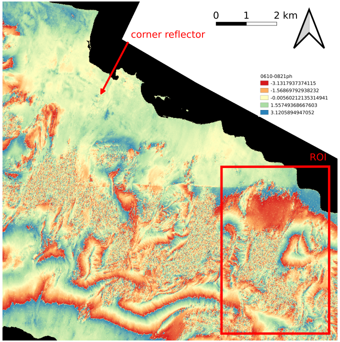
[6] Puerto Rico Quake Damage Visible From Space (Jan. 10, 2020) at
`https://www.nasa.gov/feature/jpl/puerto-rico-quake-damage-visible-from-space`

Application example: Arctic regions

- Challenge: SRTM (Shuttle RADAR Topography Mission) only covers $\pm 60°$ latitude
- Optical (ASTER) derived DEMs are poor in snow-covered, low features Arctic regions [7]
- Need to use a custom DEM [8]: `https://geodata.npolar.no/` (79°N)





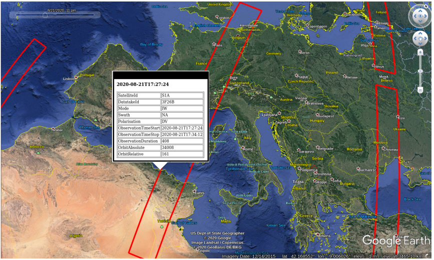


[7] T. Toutin, *ASTER DEMs for geomatic and geoscientific applications: a review*, International Journal of Remote Sensing **29** (7) 1855–1875 (2008) at `https://www.tandfonline.com/doi/full/10.1080/01431160701408477`

[8] Norwegian Polar Institute, *Terrengmodell Svalbard (S0 Terrengmodell) [Data set]*, Norwegian Polar Institute. `https://doi.org/10.21334/npolar.2014.dce53a47` (2014)

Sentinel 1 corner reflector cooperative target

- Corner reflector = localized cooperative target whose RADAR Cross Section (RCS) is larger than the surrounding scatterers in the 5 m$\times$20 m pixel
- Corner reflector only reflects incoming wave in the direction it is facing $\Rightarrow$ satellite position in the sky ?
- Maximum reflected power at 35° from the bottom plate $\Rightarrow$ satellite elevation in the sky ?

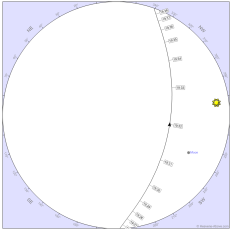


Search period start: 18 August 2020 00:00 < >
Search period end: 28 August 2020 00:00
Orbit: 695 x 696 km, 98.2° (Epoch: 06 December)

Passes to include: visible only all

Click on the date to see the ground track during the pass.

Date	Brightness	Start			Highest point			End			Pass type
	(mag)	Time	Alt.	Az.	Time	Alt.	Az.	Time	Alt.	Az.	
20 Aug	-	20:26:52	10°	WSW	20:29:25	14°	W	20:32:00	10°	NW	daylight
21 Aug	-	06:43:20	10°	NE	06:45:59	15°	E	06:48:37	10°	ESE	daylight
21 Aug	-	08:19:23	10°	N	08:24:07	72°	WNW	08:28:49	10°	SSW	daylight
21 Aug	-	09:59:37	10°	NW	10:00:52	11°	NW	10:02:06	10°	WNW	daylight
21 Aug	-	17:50:58	10°	ESE	17:54:40	24°	ENE	17:58:25	10°	N	daylight
21 Aug	-	19:27:28	10°	S	19:32:00	47°	W	19:36:36	10°	NNW	daylight



1. Identify track covering the area of interest (KML [9] from ESA)
2. Identify orbit from Heavens Above ...
3. ... in this pass: West-facing, 47° elevation $\Rightarrow$ raise the corner reflector by 12°

[9] sentinel.esa.int/web/sentinel/missions/sentinel-1/observation-scenario/acquisition-segments

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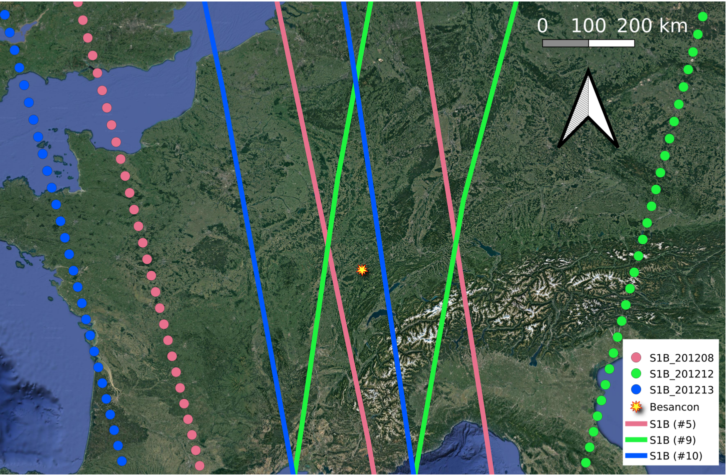
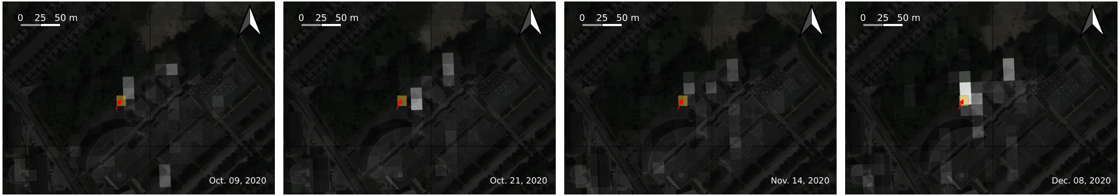
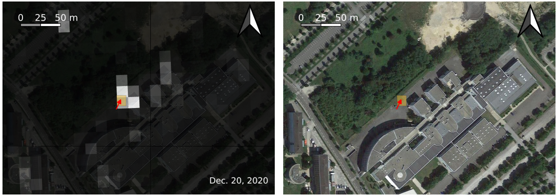
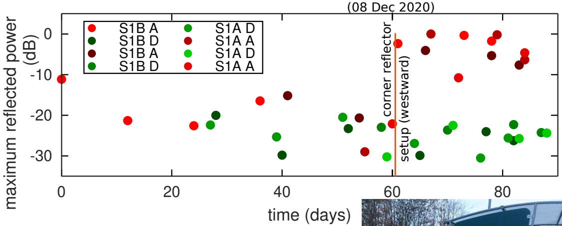


- Passes are selected as ascending (S-N) or descending (N-S) ...
- ... illuminating from the opposite direction the corner reflector
- Two Line Element (TLE) fetched on Celetrak at `https://www.celestrak.com/NORAD/elements/table.php?tleFile=active`
- ground track of the orbit using `https://github.com/anoved/Ground-Track-Generator` with `./gtg --input ../sentinel1b.tle --output S1B_201208.shp --start "2020-12-08 16:0:0.0 UTC" --end "2020-12-08 19:0:0.0 UTC" --interval 5s`
- side-looking RADAR

Sentinel 1 corner reflector



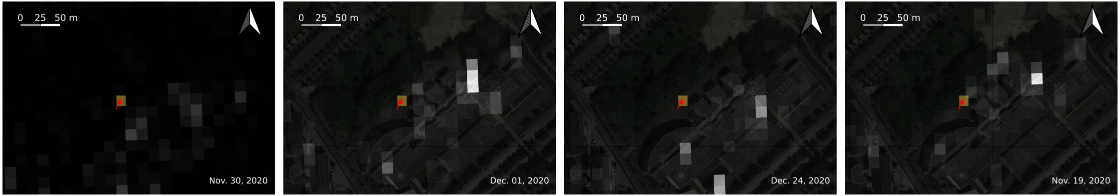


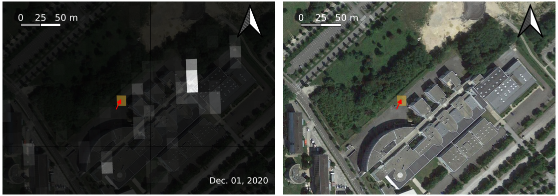


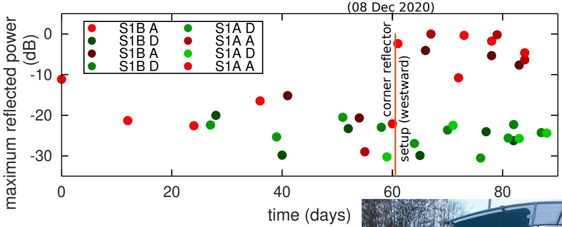
- Square trihedral: $RCS = 12 \times \pi L^4/\lambda^2 = 12200$ m^2 (L=edge length)
  Triangle trihedral: $RCS = 4/3 \times \pi L^4/\lambda^2 = 1400$ m^2
  Sphere: $RCS = \pi R^2 = 13$ m^2 if $R = 2$ m (car)
- Objective: localized displacement measurement using interferometry (phase) from the corner reflector only ($\neq$ average over pixel area)

M.C. Garthwaite & al., *The Design of Radar Corner Reflectors for the Australian Geophysical Observing System – A single design suitable for InSAR deformation monitoring and SAR calibration at multiple microwave frequency bands*, Record 2015/03 whose equation on p.27 is corrected in R. SaratPulapa & al, *Corner reflectors pattern study with & without orthogonality errors*, 13th International Conference on Electromagnetic Interference and Compatibility (INCEMIC), pp.196–201 (2015)

Sentinel 1 corner reflector







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- Objective: localized displacement measurement using interferometry (phase) from the corner reflector only ($\neq$ average over pixel area)

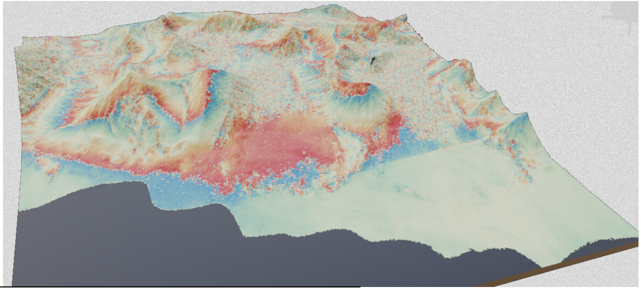
M.C. Garthwaite & al., *The Design of Radar Corner Reflectors for the Australian Geophysical Observing System – A single design suitable for InSAR deformation monitoring and SAR calibration at multiple microwave frequency bands*, Record 2015/03 whose equation on p.27 is corrected in R. SaratPulapa & al, *Corner reflectors pattern study with & without orthogonality errors*, 13th International Conference on Electromagnetic Interference and Compatibility (INCEMIC), pp.196–201 (2015)

Conclusion

- Operational flowchart for processing Sentinel-1 RADAR datasets available from ESA
- Intensity, correlation and phase provide remote sensing information on electromagnetic wave interaction with the Earth surface
- Sub-cm displacement measurement
- Deployment of a corner reflector acting as cooperative target, leading to a strong reflected intensity enhancement

Perspectives

- assess long term reproducibility and measurement errors (atmosphere)
- rugged corner reflector setup for outdoor deployment (Arctic region ?)
- cooperative target for sensing purpose [9] ?



[9] J.-M Friedt, *Wideband measurement strategies: from RADAR to passive wireless sensors ... and how passive wireless sensors were/are used by intelligence agencies*, FOSDEM (2016)

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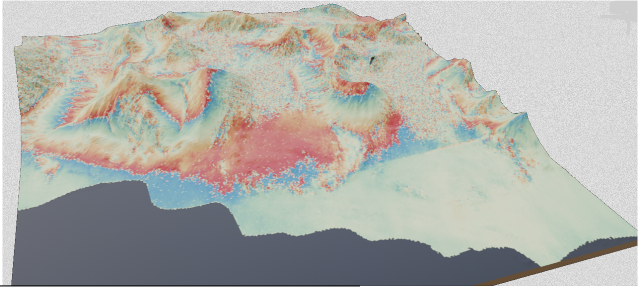

[9] J.-M Friedt, P. Abbé, *Parler à un RADAR spatioporté : traitement et analyse des données de Sentinel1*, GNU/Linux Magazine France 246 (March 2021)