Processing raw (level0) Sentinel1 spaceborne RADAR signals

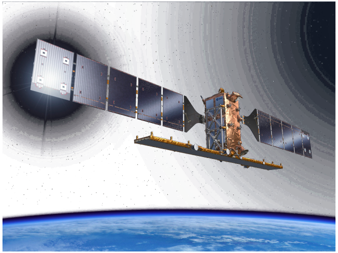


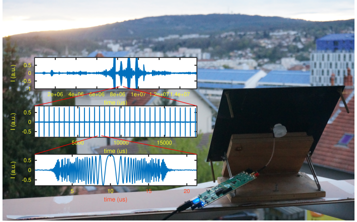
Image from `www.esa.int/`

J.-M Friedt

FEMTO-ST
Time & Frequency department

jmfriedt@femto-st.fr

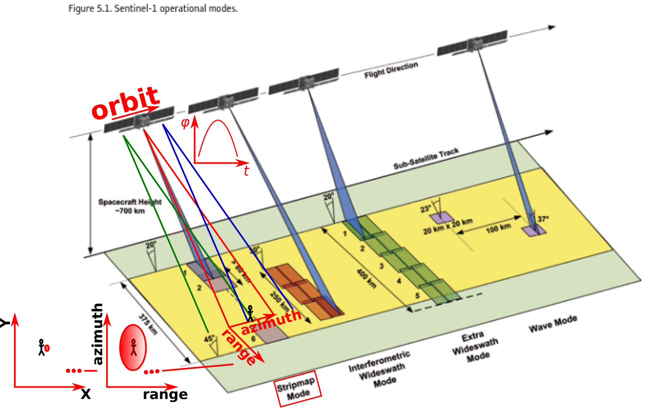
slides at `jmfriedt.free.fr`



Sequel to J.M. Friedt, P. Abbé, *Talking to spaceborne RADAR: Sentinel1 data processing*, FOSDEM2021 at `fosdem.org/2021/schedule/event/frs_talking_to_spaceborne_radar_sentinel1_data_processing/`

June 6, 2021

Spaceborne Synthetic Aperture RADAR



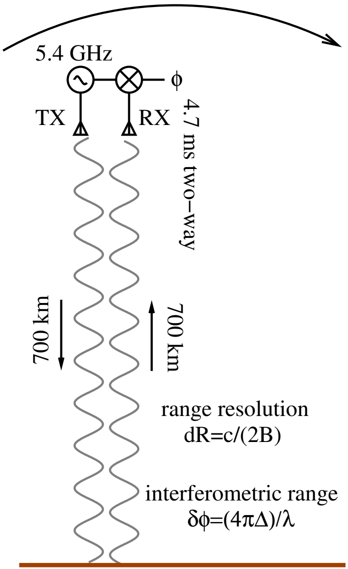
- RADAR: all-weather, day & night observation (active illumination)
- C-band: frequency 5404 ± 50 MHz ($\lambda \simeq 5.6$ cm)
- 700 km altitude, 98.6 minute orbit, polar orbiting/Sun synchronous
- 12-day repetition for each satellite (Sentinel 1A, Sentinel 1B)
- Radiofrequency: access to the *phase* 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]

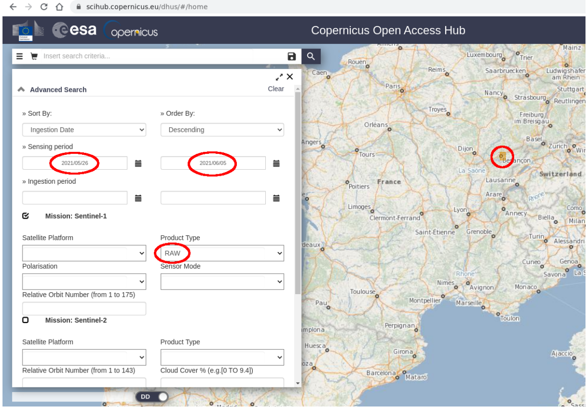
- Chirped emission: range compression
- Moving RADAR source along satellite orbit: azimuth compression
- Pixel size: 5 m$\times$20 m
- Phase measurement: interferometry for sub-wavelength displacement analysis
- Orbit designed to repeat observation geometry every 12 days: InSAR (Interferometric Synthetic 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
- **raw information provided by ESA**: IQ datastream

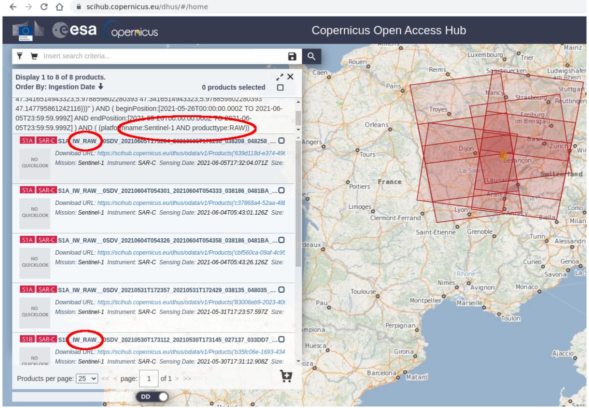


[1] J.A. Johannessen & F. Collard, *SAR Instrument Principles and Processing* (2012) at https://earth.esa.int/eogateway/documents/20142/0/01_Wednesday_OCT2013_SAR_principles.pdf

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) or StripMap (SM) RAW datasets

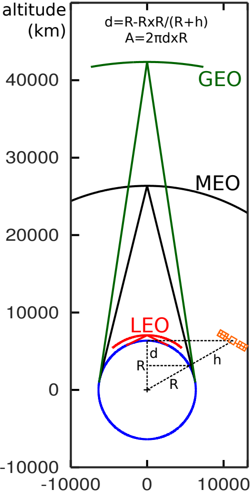


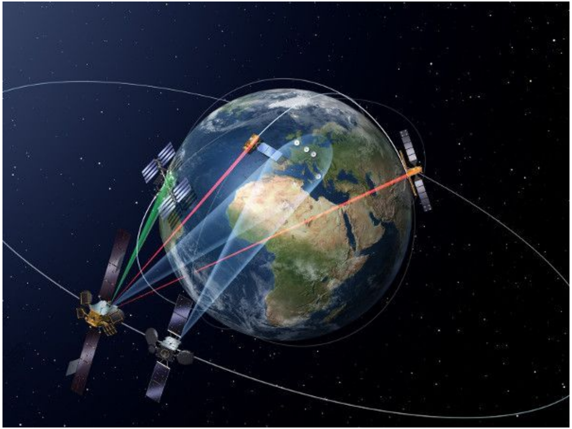


- Each satellite flies over Besançon every 3 or 4 days (red)
- observation path prediction (ascending and descending) provided as KML files at [2]

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

Challenge of Low Earth Orbit (LEO) communication [3]





- ESA receivers in Redu (Belgium), Harwell United Kingdom) and Weilheim (Germany)
- https://earth.esa.int/web/eoportal/satellite-missions/e/edrs: "two geostationary data relay satellites, intended to provide links to satellites in LEO satellites [...] enabling real-time communications between these spacecraft and their respective Control Center."

Earth surface: $S = 4\pi R_{Earth}^2 = 5.1 \cdot 10^8$ km^2
LEO at 700 km: $A/S = 5\%$; MEO at 20000 km: $A/S = 38\%$; GEO at 36000 km: $A/S = 42\%$

[3] Illustration from https://artes.esa.int/edrs/overview

Communication from space to ground

Low Earth orbiting satellite (high resolution imaging):

- low coverage, only 5% of the surface of the Earth visible at any given time
- continuous streaming of data collected by Sentinel1 (50 MHz/10 bit/IQ$\simeq$200 MB/s) + low latency (Airbus Defence) $\Rightarrow$ optical link from Sentinel1 to EDRS[4] (geostationnary) and EDRS to Germany
- packetized communication: CCSDS packets available from ESA Copernicus Hub web site (encrypted + error corrected stream to Earth)
- each packet identifies which instrument from which spaceborne platforms (Sentinels, ISS, LEO satellites) is transmitting before sending the payload.

For the interpretation of the binary code in the N-BIT FIELD the first bit ("Bit 0") is the most significant bit (msb), the last bit ("Bit N-1") is the least significant bit (lsb).

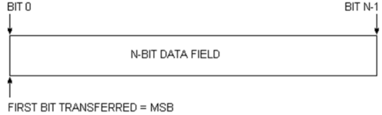
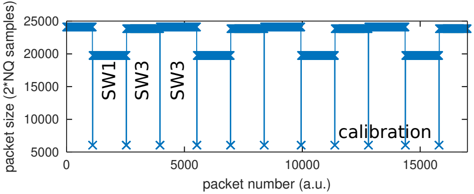


Fig. 1-1: Bit Numbering Convention

```
jmfriedt@rugged:/tmp$ xxd s1b-iw-raw-s-vv-20210216t083028-20210216t083100-025629-030def.dat | head -5
00000000: 0c1c eb95 4b15 4d56 4536 6e01 352e f853  ....K.MVE6n.5..S
00000010: 061b de80 0800 0000 0001 11c5 d300 03ab  ................
00000020: 9500 03b6 b80c 1f00 0808 8645 302f 0007  ..........E0/..
00000030: af09 0055 6300 11a8 0036 4a7c 6181 0600  ...Uc....6J|a...
00000040: 0a2e 5d00 03dc 0528 bc9a b264 3817 302b  ..]....(...d8.0+
```



[4] European Data Relay Satellite System Overview: `https://artes.esa.int/edrs/overview`

Communication from space to ground

Low Earth orbiting satellite (high resolution imaging):

- continuous streaming of data collected by Sentinel1 (50 MHz/10 bit/IQ$\simeq$200 MB/s) + low latency (Airbus Defence) $\Rightarrow$ optical link from Sentinel1 to EDRS[4](geostationnary) and EDRS to Germany
- packetized communication: CCSDS packets available from ESA Copernicus Hub web site (encrypted + error corrected stream to Earth)
- each packet identifies which instrument from which spaceborne platforms (Sentinels, ISS, LEO satellites) is transmitting before sending the payload.

H. Flachs, *Sentinel-1 SAR Instrument – SAR Space Packet Protocol Data Unit*, ESA (22/05/2015) at `https://sentinel.esa.int/documents/247904/2142675/Sentinel-1-SAR-Space-Packet-Protocol-Data-Unit.pdf/d47f3009-a37a-43f9-8b65-da858f6fb1ca?t=1547146144000`

For the interpretation of the binary code in the N-BIT FIELD the first bit ("Bit 0") is the most significant bit (msb), the last bit ("Bit N-1") is the least significant bit (lsb).

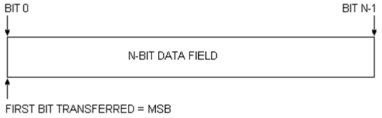
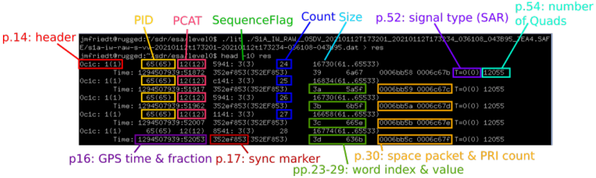
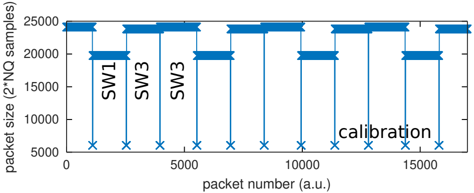


Fig. 1-1: Bit Numbering Convention

Pages refer to "Sentinel1 SAR Space Packet Protocol Data Unit S1-IF-ASD-PL-0007"





Decoding CCSDS packets

- No need to bother with the physical layer, soft to hard bit conversion and data consistency
- fixed field width with a synchronization word for alignement
- payload is compressed with Flexible Dynamic Block Adaptive Quantizer (FDBAQ [5]) selecting amongst 5 Huffman trees depending on the information content

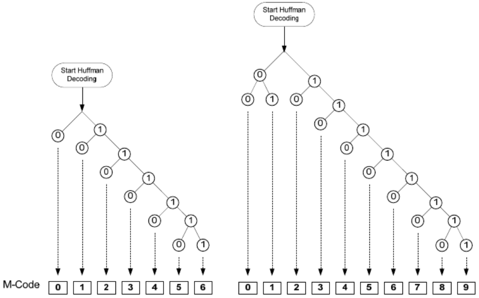
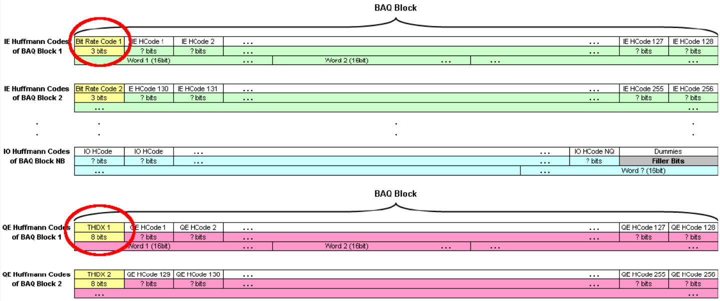


Fig. 4-9: Huffman Decoding for BRC=2, (k=7) Fig. 4-10: Huffman Decoding for BRC=3, (k=10)



[5] E. Attema & al., *Sentinel-1 Flexible Dynamic Block Adaptive Quantizer*, Proc. 8th European Conference on Synthetic Aperture Radar (EUSAR), July 2010 at `https://www.researchgate.net/publication/224233683_Sentinel-1_Flexible_Dynamic_Block_Adaptive_Quantizer`

Raw telemetry and data

Primary and secondary headers properly decoded, packet size, satellite attitude (red) and radiofrequency pulse changing with each swath (red):

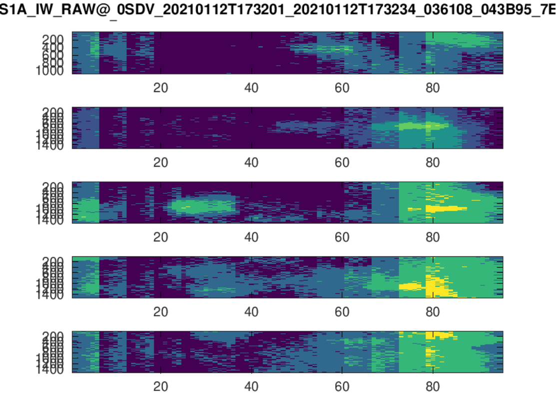
```
0c1c: 1(1) 65(65) 12(12) 254c: 3(3) Count=11 Len=19494(61..65533)
Time: 1306431091:19852 352ef853(352EF853) WordIndex=31 WordVal=575e 00044b0b 0004562e BAQ=0c(c)
BlockLen=1f(1F)
Decim=b TXPRR=8488=1160 TXPSF=-0x2932=10546 TXPL=00000917=2327 PRI=00006501=25857 Polar=7
Typ=0(0) Swath=b NQ=12055
finished processing 19432 echo

0c1c: 1(1) 65(65) 12(12) d94b: 3(3) Count=12 Len=19418(61..65533)
Time: 1306431091:19897 352ef853(352EF853) WordIndex=32 WordVal=5d57 00044b0c 0004562f BAQ=0c(c)
BlockLen=1f(1F)
Decim=b TXPRR=8488=1160 TXPSF=-0x2932=10546 TXPL=00000917=2327 PRI=00006501=25857 Polar=7
Typ=0(0) Swath=b NQ=12055
finished processing 19356 echo
```

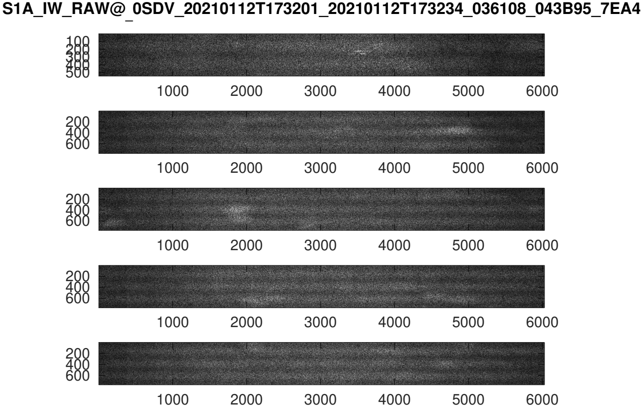
output of `https://github.com/jmfriedt/sentinel1_level0`

Data consistency assessment: compression ratio

- Compression ratio depends on features of the reflected signals
- Urban areas will require more structure than forest or water covered areas



Bit Rate Code (BRC) mapping [6]



Reflected intensity

[6] P. Guccione & al., *Sentinel-1A: Analysis of FDBAQ Performance on Real Data*, IEEE Transactions on Geoscience and Remote Sensing, December 2015, DOI: 10.1109/TGRS.2015.2449288 at `https://www.researchgate.net/publication/281607948_Sentinel-1A_Analysis_of_FDBAQ_Performance_on_Real_Data`

Data consistency assessment: range compression [7]

- Synthetic aperture RADAR (SAR) signals encode longitude in range information and latitude into azimuth
- $\Rightarrow$ range and azimuth compression to accumulate energy on each signal reflected by each target
- Range compression requires knowledge of the transmitted pulse: parameters provided in the Sentinel1 telemetry:
- successful range compression demonstrates proper decoding

Nominal Image Replica Generation

The nominal image replica is generated from the nominal image phase coefficients array which is a configurable input parameter. The nominal image replica at sample time t_n is generated as:

$$NomChirp_{image}(t_n) = \frac{1}{n_{samples}} \cdot \exp\left[2\pi j \cdot \left(\varphi(1) \cdot t_n + \varphi(2) \cdot t_n^2\right)\right],$$
$$n = \frac{-TXPL}{2}, \ldots, \frac{TXPL}{2} - 1 \qquad (4\text{-}24)$$

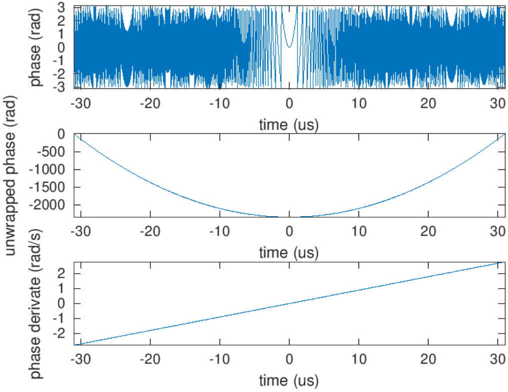
where φ is an array of four configurable chirp phase coefficients nominally defined as:

- $\varphi(0) = 0$
- $\varphi(1) = TXPSF - TXPRR \cdot \frac{-TXPL}{2}$
- $\varphi(2) = \frac{TXPRR}{2}$
- $\varphi(3) = 0$

[7] R. Piantanida, *Level 1 Detailed Algorithm Definition*, ESA (07/06/2019), p.4-6 at `https://sentinel.esa.int/documents/247904/1877131/Sentinel-1-Level-1-Detailed-Algorithm-Definition`

Data consistency assessment: range compression [7]

- Synthetic aperture RADAR (SAR) signals encode longitude in range information and latitude into azimuth
- $\Rightarrow$ range and azimuth compression to accumulate energy on each signal reflected by each target
- Range compression requires knowledge of the transmitted pulse: parameters provided in the Sentinel1 telemetry:
- successful range compression demonstrates proper decoding

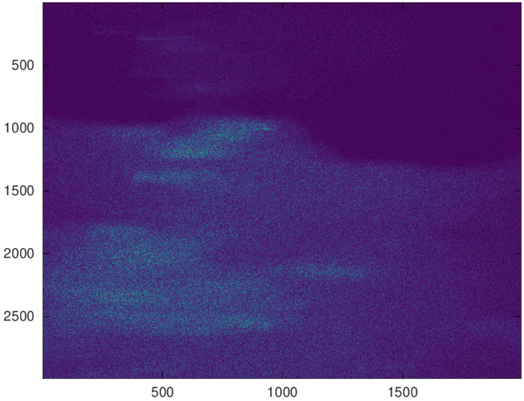


Wrapped and unwrapped phase v.s time (position)

[7] R. Piantanida, *Level 1 Detailed Algorithm Definition*, ESA (07/06/2019), p.4-6 at `https://sentinel.esa.int/documents/247904/1877131/Sentinel-1-Level-1-Detailed-Algorithm-Definition`

Data consistency assessment: range compression [7]

- Synthetic aperture RADAR (SAR) signals encode longitude in range information and latitude into azimuth
- $\Rightarrow$ range and azimuth compression to accumulate energy on each signal reflected by each target
- Range compression requires knowledge of the transmitted pulse: parameters provided in the Sentinel1 telemetry:
- successful range compression demonstrates proper decoding

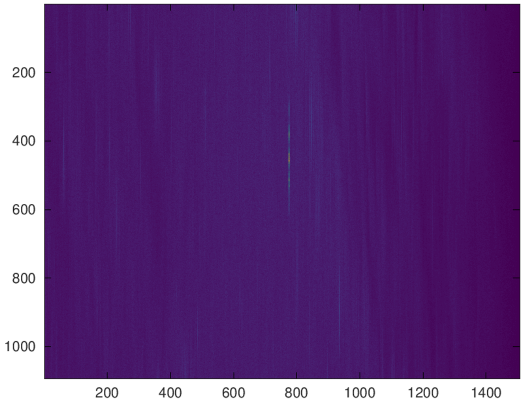


Before compression: energy spread along range and azimuth

[7] R. Piantanida, *Level 1 Detailed Algorithm Definition*, ESA (07/06/2019), p.4-6 at `https://sentinel.esa.int/documents/247904/1877131/Sentinel-1-Level-1-Detailed-Algorithm-Definition`

Data consistency assessment: range compression [7]

- Synthetic aperture RADAR (SAR) signals encode longitude in range information and latitude into azimuth
- $\Rightarrow$ range and azimuth compression to accumulate energy on each signal reflected by each target
- Range compression requires knowledge of the transmitted pulse: parameters provided in the Sentinel1 telemetry:
- successful range compression demonstrates proper decoding



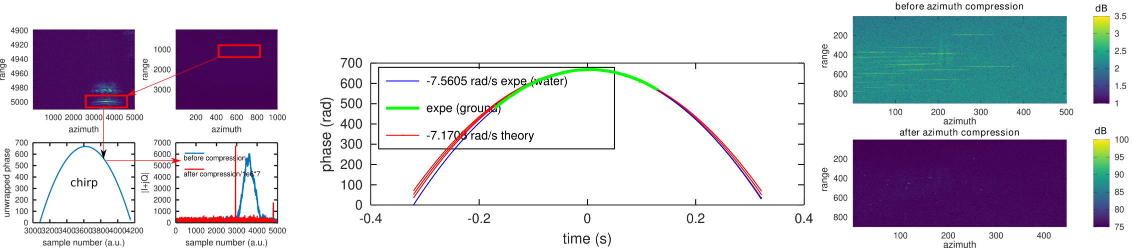
Cross-correlation of the pulse-shape with the image along the range direction (X-axis)

[7] R. Piantanida, *Level 1 Detailed Algorithm Definition*, ESA (07/06/2019), p.4-6 at
`https://sentinel.esa.int/documents/247904/1877131/Sentinel-1-Level-1-Detailed-Algorithm-Definition`

Data consistency assessment: azimuth compression

Even with no knowledge of spaceborne SAR azimuth compression

- select a strong point-like target (Dirac convolution of the incoming pulse)
- unwrap phase along azimuth around this target
- correlate along azimuth with this pulse shape for azimuth pulse compression ($\perp$ range)



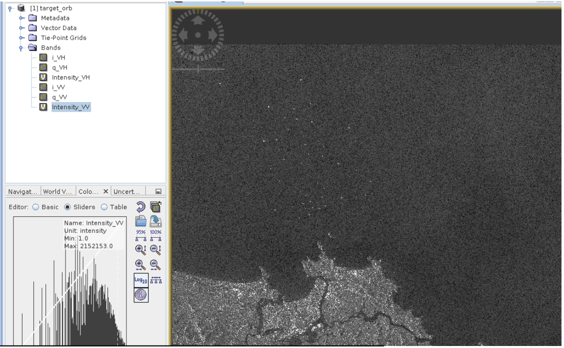
- Energy spread along azimuth direction collapses in a single point (ships waiting in the harbour of Sao Paolo): successful azimuth compression

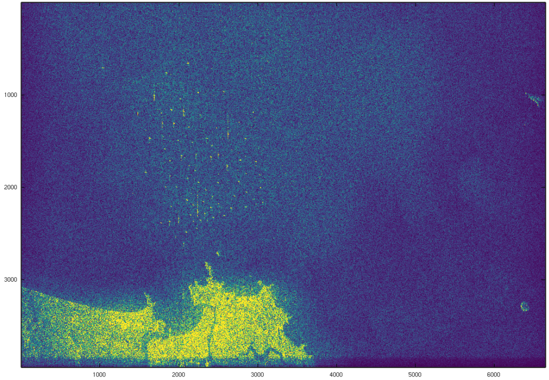
Data consistency assessment: azimuth compression

- Each line starts after a Pulse Repetition Interval (PRI) from the previous ($\simeq$ sampling frequency)
- PRI given in the telemetry data (StripMap: $PRI = 1/1663.5$ Hz)
- According to [8], the phase of the pulse reflected from ground is developed as a second order Taylor series determined by range to ground R_0 and derivates

$$\varphi \propto R_0 + \dot{R} \times s + \ddot{R}/2 \times s^2 \text{ along position } s \text{ and } \ddot{R} = v_e^2/R_0 \text{ with } v_e = v_s/\left(\sqrt{1 + Hleo/REarth}\right)$$

- with $\ddot{R}$ depending on the satellite velocity identified using Kepler's law T^2/R^3 =constant ($T = 5921$ s in agreement with Celestrak TLE)

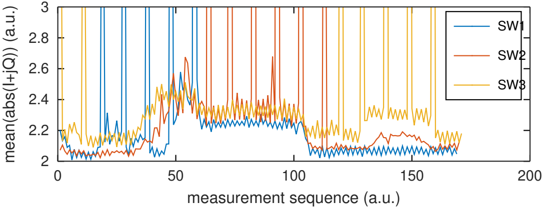


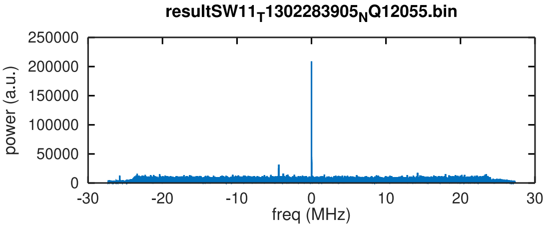


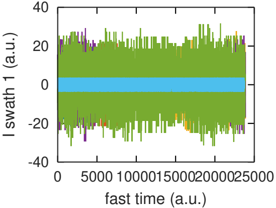
[8] D. Sandwell *& al.*, *GMTSAR: An InSAR Processing System Based on Generic Mapping Tools (2nd Ed.)*, pp.51–59 (2016), at `https://topex.ucsd.edu/gmtsar/tar/GMTSAR_2ND_TEX.pdf`

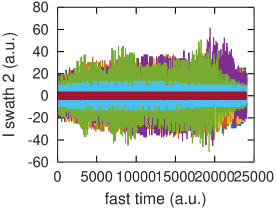
Beyond RADAR processing: rank echoes

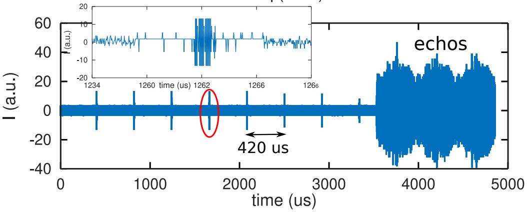
- Sentinel1 starts recording as soon as the first pulse is transmitted
- Two-way time of flight: emission at an angle of $\simeq 45^\circ$ from 700 km altitude=two way path of $2 \times 700/\cos(45^\circ) = 1980$ km traveled in 6600 μs or $\simeq 11$ echoes at a PRI of 1/1600 Hz=625 μs
- **Rank echoes**: period of silence when the RADAR operates as radiometric measurement
- Detect ground based emitters (weather/C-band and military G-band emitters)
- Doppler shift/wind speed analysis





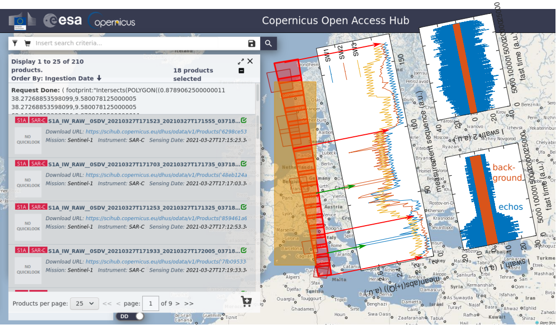




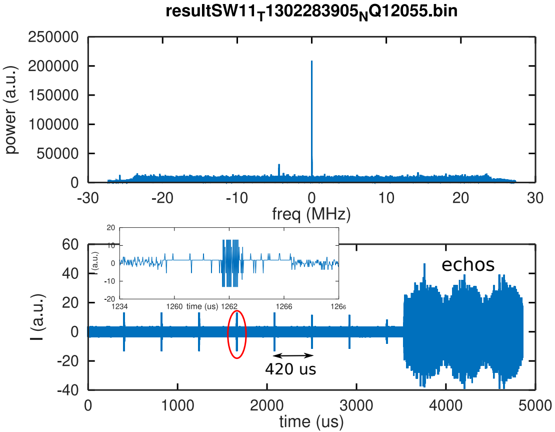


Beyond RADAR processing: rank echoes

- Sentinel1 starts recording as soon as the first pulse is transmitted
- Two-way time of flight: emission at an angle of $\simeq 45°$ from 700 km altitude=two way path of $2 \times 700/\cos(45°) = 1980$ km traveled in 6600 μs or $\simeq 11$ echoes at a PRI of 1/1600 Hz=625 μs
- **Rank echoes**: period of silence when the RADAR operates as radiometric measurement
- Detect ground based emitters (weather/C-band and military G-band emitters)
- Doppler shift/wind speed analysis

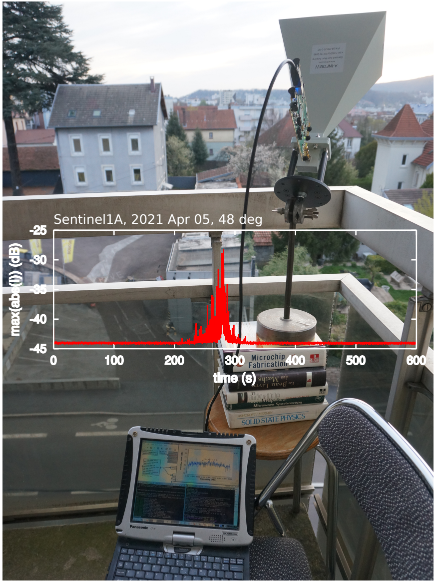


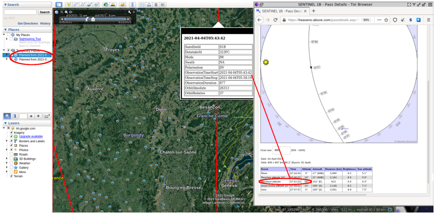
A. Monti-Guarnieri, *Identification of C-Band Radio Frequency Interferences from Sentinel-1 Data*, MDPI Remote Sensing **9** (11), 1183 (2017) at `https://www.mdpi.com/2072-4292/9/11/1183`

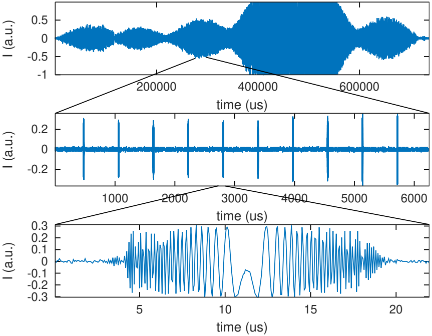


Passive RADAR processing

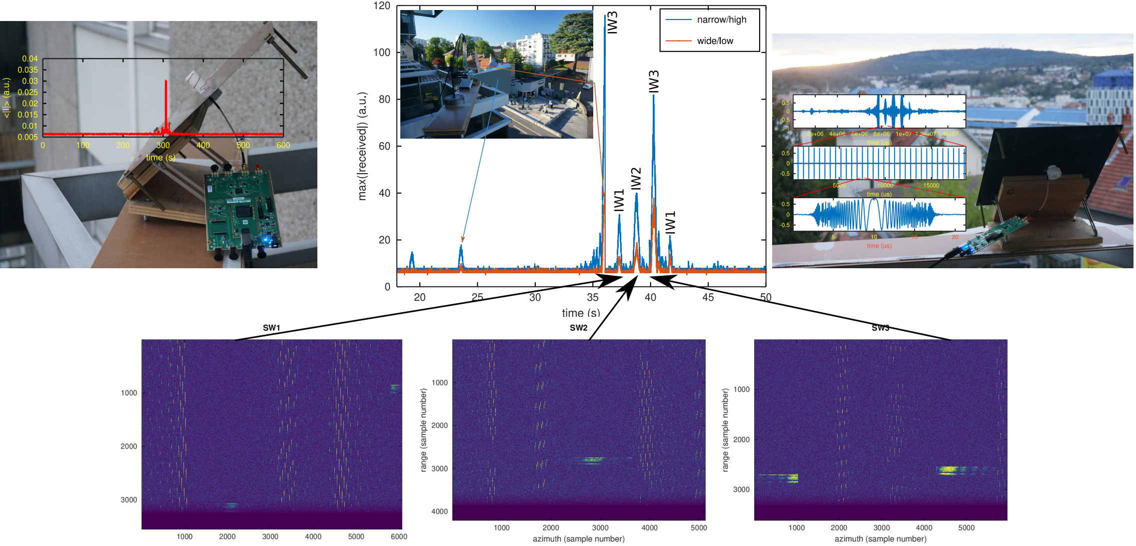
- Preliminary investigation of the raw radiofrequency signal collected from ground and reflected by ground based targets
- Pulse Repetition Interval provided by telemetry
- Multiple swaths are detected in the reflected signals







Passive RADAR processing

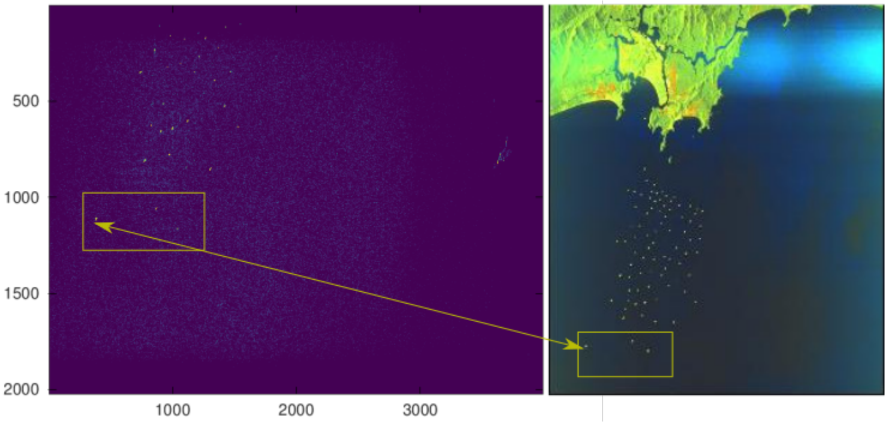


Identification of which Swath emission illuminated the receiving antenna during the pass (PRI analysis)

Conclusion

- First free, opensource software for decoding raw Sentinel1 level0 data provided by ESA
- Consistency demonstrated with range and azimuth compressed data matching ESA level1 results

  `https://github.com/jmfriedt/sentinel1_level0`
- usage demonstrated beyond SAR analysis: ground based emissions detected in rank echoes



Perspective

- passive RADAR processing

Acknowledgement: the author of `https://github.com/plops/cl-cpp-generator2/blob/master/example/` provided invaluable support (`08_copernicus_radar/source`) and initial insight in data processing.