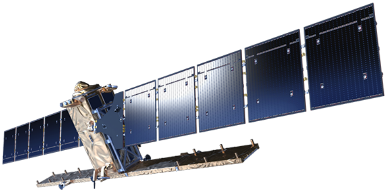
Passive bistatic RADAR using spaceborne Sentinel1 non-cooperative source, a B210 and a Raspberry Pi4



https://amt4sentinelfrm.org/

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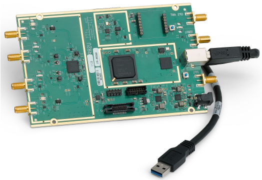
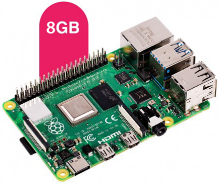




https://www.ettus.com/
https://www.kubii.fr/

Slides at http://jmfriedt.free.fr/grcon2021.pdf
sequel to European GNU Radio Days: http://jmfriedt.free.fr/gnuradiodays_setinel1_level0.mp4

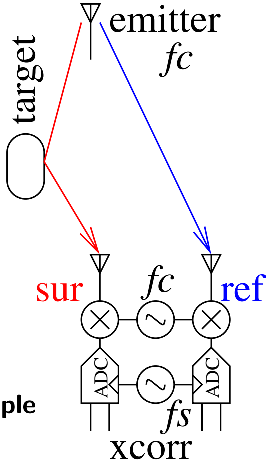
August 12, 2021

Passive bistatic RADAR (PBR)

- Passive RADAR: using existing electromagnetic sources for RAdiofrequency Detection And Ranging (time delay and Doppler shift for target velocity)
- Popular with universities and amateurs: no need to be allowed to emit a strong signal ($P_R \propto P_E/d^4$)
- Range resolution solely determined by bandwidth Δf
  $\Delta R = c/(2\Delta f) \Rightarrow \Delta f \nearrow \Rightarrow \Delta R \searrow$
- Beamwidth $\simeq$ azimuth resolution determined by antenna size wrt λ
- Sythetic Aperture RADAR: move transmitting and/or receiving antenna to simulate a large aperture and hence improved azimuth resolution

Demonstrated using Ettus Research E312 or [1] B210 [2] [3] SDR platforms using frequency stacking.

Need for two coherent (same LO, same sampling rate) channels to sample reference and surveillance signals



[1] S.T. Peters *& al.*, *In Situ Demonstration of a Passive Radio Sounding Approach Using the Sun for Echo Detection*, IEEE Trans. Geosci. and Remote Sensing **56** (12) 7338 (Dec. 2018)

[2] S. Prager *& al.*, *Ultrawideband Synthesis for High-Range-Resolution Software-Defined Radar*, IEEE Trans. Instrum. Meas. **69** 3789-–3803 (2020)

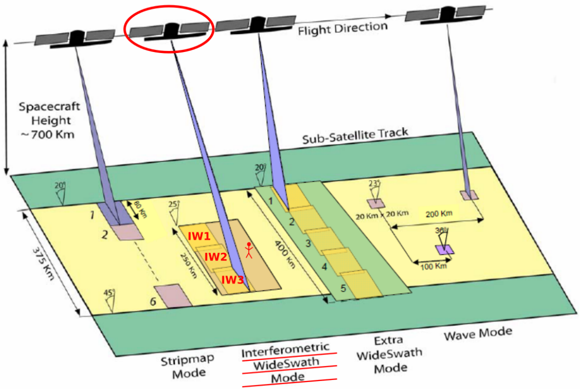
[3] O. Toker *& al.*, *A Synthetic Wide-Bandwidth Radar System Using Software Defined Radios*, 7th International Electronic Conference on Sensors and Applications (15–30 November 2020)

Spaceborne RADAR as PBR non-cooperative source

Most common: static emitter (e.g. DVB-T or GSM tower) and moving receiver(s)

Here: spaceborne ESA Sentinel1 RADAR

- 693 km altitude, 14.59 revolutions/day [4](98.7 min/orbit)
- emitting 4.7 kW peak power chirps in C-band (5405$\pm$30 MHz) within carrier range of AD9361 (B210 frontend), 60 MHz BW
- available at any landmass location over the Earth, repeat time = 6 days (two satellites)
- Interferometric Wide (IW) Swath TOPSAR measurement: successive bursts along successive swaths
- Satellite motion along its path = spatial diversity for azimuth compression



https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar/sar-instrument/acquisition-modes

Different parameters for each sub-swath: which one to use?

Usually, the satellite emits and receives its own signal while flying over a given spot: **can we use this signal for PBR?**

[4]NORAD TLE

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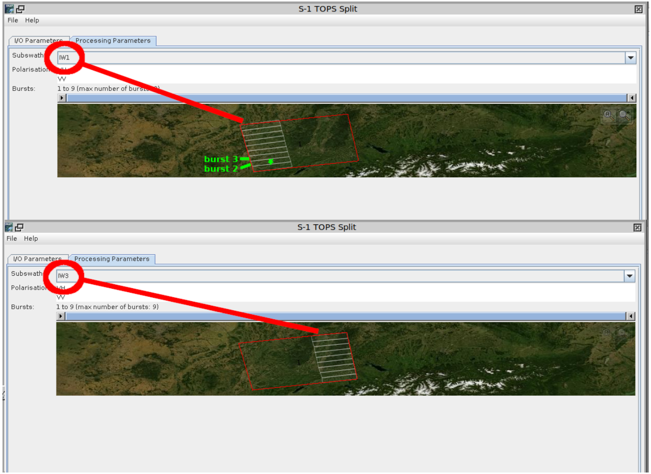


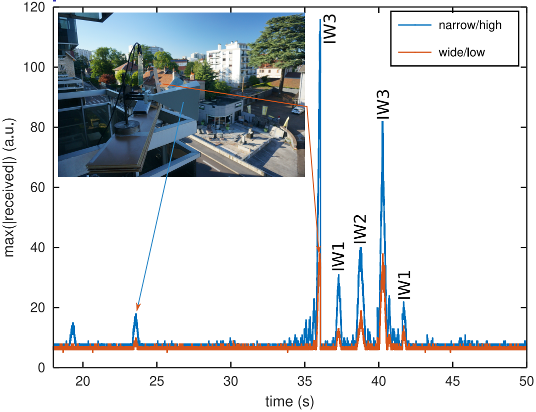
SNAP TOPSAR Split user interface showing Swaths & Bursts

Usually, the satellite emits and receives its own signal while flying over a given spot: **can we use this signal for PBR?**

[4]NORAD TLE

Hardware for radiofrequency signal reception

- SDR: bandwidth challenge
- single channel B210 measurement: 56 Msamples/s …
- … streamed to 8 GB RAM Raspberry Pi 4 (RPi 4) and stored to RAMdisk.
- RPi4 6 GB/56 MS/s IQ bytes=57 second records
- RPi4 6 GB/2×30 MS/s IQ bytes=53 seconds
- Sentinel1 pass (Heavens Above): 9 min. horizon to horizon but a given location …
- … is only illuminated for a few seconds.
- Horn antenna: A-Infomw 20 dB gain (4.90–7.05 GHz) LB-159-20-C-SF …
- … but only 16° beamwidth.
- Helical antenna above a FR4 ground plane



Antenna: helical antenna made of 0.8 mm enameled copper wire wound on a hollow teflon cylinder 15 or 20 mm diameter D, 3–4 turns, over a 30 × 30 cm FR4 ground plane

Balanis 3rd Ed. (10.3.1 p. 566): $\frac{3}{4} < \frac{C}{\lambda} < \frac{4}{3} \Rightarrow C \in [3/4\lambda : 4/3\lambda]$ with $\lambda = 300/5405 = 5.54$ cm $\Leftrightarrow C = \pi D \in [4.2 : 7.4]$ cm $\Leftrightarrow D \in [1.3 : 2.3]$ cm and $R = 140\left(\frac{C}{\lambda}\right)$ with a pitch angle $\alpha \in [12 : 14]^\circ$

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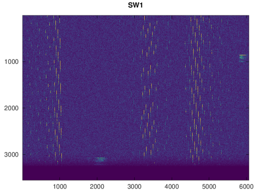

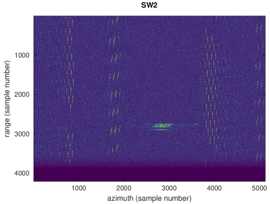

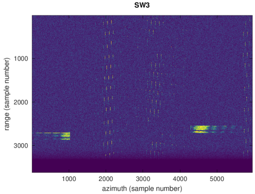

Test each possible IW swath Pulse Repetition Interval (PRI) from Level0* decoding and check which echo aligns target reflections along constant range lines

* `github.com/jmfriedt/sentinel1_level0`

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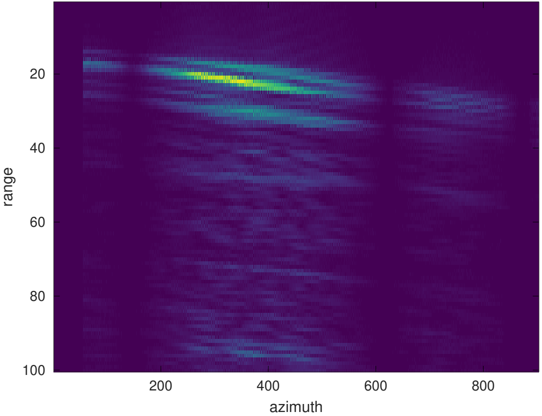
Single channel acquisition/processing

Excessive satellite motion during acquisition prevents single channel azimuth compression:

- Known Pulse Repetition Interval (PRI) and chirp characteristics from Level0 decoding [5] ⇒ reshape time-vector as matrix accordingly
- orbit circumference= $40000 + 2\pi \times 693 = 44354$ km
- linear speed=$44354/(98.7 \times 60) = 7.49$ km/s
- 37.5 km traveled along orbit during 5-s acquisition
- Strong nearby targets are not aligned at same range and azimuth compression will not occur when inverse Fourier transform along azimuth direction
- Modified[6] for dual coherent channel acquisition and storage as 8-bit complex `https://github.com/EttusResearch/uhd/blob/master/host/examples/rx_multi_samples.cpp`



Range compressed by correlating with theoretical chirp shape

⇒ mandatory **reference channel acquisition** to compensate for satellite motion during acquisition **BUT** halves the sampling rate (range resolution) to 30 MS/s ($\Delta R \simeq 5$ m)

[6] `https://github.com/jmfriedt/sentinel1_level0`

[6] `https://github.com/jmfriedt/sentinel1_pbr/blob/main/b210_to_file/rx_multi_samples.cpp`

UHD data acquisition software

- SDR: bandwidth challenge
- dual channel measurement from B210: 30 Msamples/s …
- … streamed to Raspberry Pi 4 (RPi 4) and stored to RAMdisk.
- Over The Wire (otw) 8-bit samples, storage as 8-bit IQ interleaved ⇒ 30 MS/s dual channels

```cpp
int UHD_SAFE_MAIN(int argc, char* argv[])
{
 std::string args, sync, subdev, channel_list="0,1";// RX1,2
 double seconds_in_future=1.5;                      // sync
 size_t total_num_samps=0x0ffffff0;                 // samples
 double rate=30e6,freq=5405e6,gain=70,lo_offset=0;  // fs, fc, fo, G
 uhd::usrp::multi_usrp::sptr usrp=uhd::usrp::multi_usrp::make(args);
 if (vm.count("subdev"))
    usrp->set_rx_subdev_spec(subdev); // sets across all mboards
 usrp->set_rx_rate(rate);
 uhd::tune_request_t tune_request(freq, lo_offset);
 usrp->set_rx_freq(tune_request, 0);
 usrp->set_rx_freq(tune_request, 1);
 usrp->set_rx_gain(gain, 0);
 usrp->set_rx_gain(gain, 1);
 usrp->set_time_now(uhd::time_spec_t(0.0));
 std::vector<std::string> channel_strings; // which channels to use
 std::vector<size_t> channel_nums;
 boost::split(channel_strings, channel_list, boost::is_any_of("\"',"));
 for (size_t ch = 0; ch < channel_strings.size(); ch++) {
   size_t chan = std::stoi(channel_strings[ch]);
   channel_nums.push_back(std::stoi(channel_strings[ch]));
 }
 uhd::stream_args_t stream_args("sc8","sc8"); // OTW FORMAT /!\
 stream_args.channels            =channel_nums;
 uhd::rx_streamer::sptr rx_stream=usrp->get_rx_stream(stream_args);
 uhd::stream_cmd_t stream_cmd(uhd::stream_cmd_t::STREAM_MODE_START_CONTINUOUS);
 stream_cmd.num_samps  = total_num_samps;
 stream_cmd.stream_now = false;
 stream_cmd.time_spec  = uhd::time_spec_t(seconds_in_future);
 rx_stream->issue_stream_cmd(stream_cmd); // all channels stream
 uhd::rx_metadata_t md; // meta-data will be filled in by recv()
 const size_t samps = rx_stream->get_max_num_samps();
 std::vector<std::vector<std::complex<char>>> buffs(
   usrp->get_rx_num_channels(), std::vector<std::complex<char>>(samps));
 std::vector<std::complex<char>*> buff_ptrs; // vector of pointers to each channel
 for (size_t i = 0; i < buffs.size(); i++)
    buff_ptrs.push_back(&buffs[i].front());
 double timeout = seconds_in_future + 0.1;   // timeout
 std::ofstream outfile1, outfile2;
 outfile1.open("/tmp/1.bin", std::ofstream::binary);
 outfile2.open("/tmp/2.bin", std::ofstream::binary);
 size_t num_acc_samps = 0; // number of accumulated samples
 for (int jmf=0;jmf<6;jmf++)   // 8 GB RPi4
   {num_acc_samps = 0; // number of accumulated samples
    while (num_acc_samps < total_num_samps) {
      // receive a single packet
      size_t num_rx_samps = rx_stream->recv(buff_ptrs, samps, md, timeout);
      timeout = 0.1;
      outfile1.write( (const char*)&buffs[0].front(), samps*sizeof(std::complex<char>));
      outfile2.write( (const char*)&buffs[1].front(), samps*sizeof(std::complex<char>));
      num_acc_samps += num_rx_samps;
    }
   }
 if (outfile1.is_open()) { outfile1.close(); }
 if (outfile2.is_open()) { outfile2.close(); }
}
```

Where does the signal come from?

Oblique illumination at $\simeq 45^\circ \Rightarrow$ satellite over Brittany when illuminating East of France ($\simeq$ 700 km to the East) during an ascending pass [7] ($693/\cos(45^\circ) = 980$ km electromagnetic wave path)

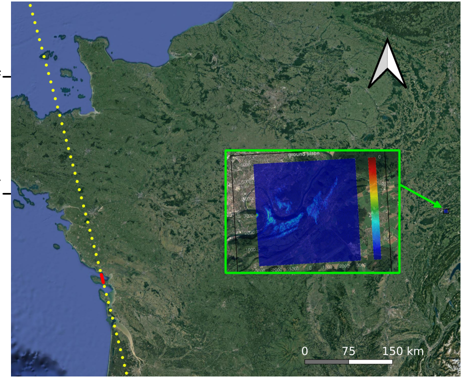
- Exact acquisition time known from previous pass filename:
- raw Level0 dataset

`S1A_IW_RAW__0SDV_20210519T172356_20210519T172429_037960_047AF4_`
was acquired May 19, 2021 from 17:23:56 to 17:24:29 UTC (33 s duration)

- IW SLC Level1 dataset

`S1B_IW_SLC__1SDV_20210705T173118_20210705T173144_027662_034D27_`
was acquired May 7, 2021 from 17:31:18 to 17:31:44 (16 s duration)

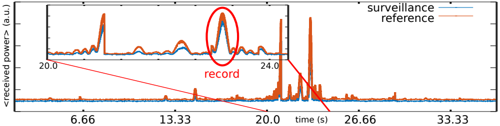
- 6 GB RAMdisk on the 8 GB Raspberry Pi 4 holds 53 s $\gg$ 33 or 16 s: longer acquisition spanning the expected time.
- Ascending pass illuminating eastward so reference antenna facing westward and echoes collected by surveillance antenna facing the East.

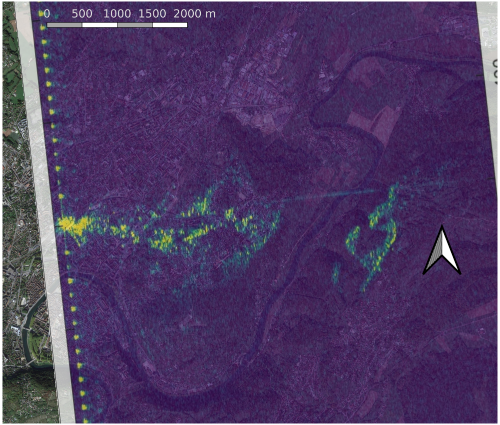


[7] https://github.com/anoved/Ground-Track-Generator

Passive bi-static measurement using Sentinel1 spaceborne RADAR as non-cooperative source

reference antenna





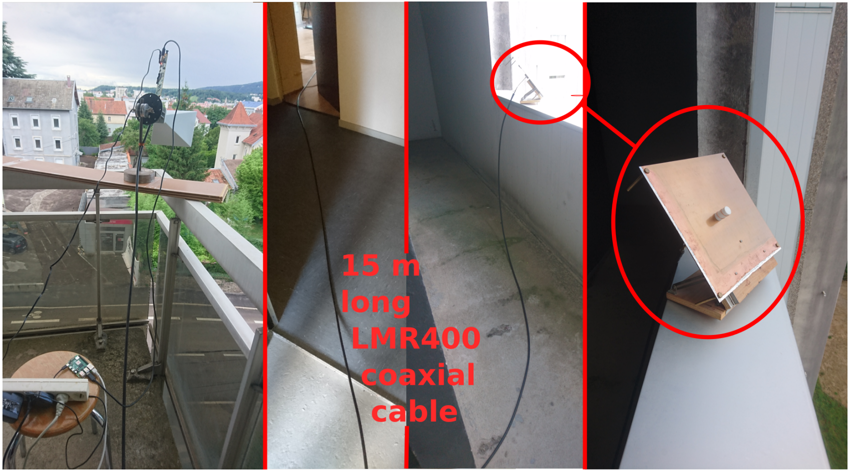
surveillance antenna

- 0.5-second usable record (30 MS/s$\times$2 channels)
- Understanding level0 allows splitting datastream according to Pulse Repetition Interval
- Range compression by correlation of reference and surveillance channels
- Range axis determined by illumination geometry: $dr = c \times dt/(1 + cos\vartheta)$
- Azimuth compression by inverse Fourier transform

See A. Anghel *& al.*, *Bistatic SAR imaging with Sentinel-1 operating in TOPSAR mode*, 2017 IEEE Radar Conference

Experimental setup

- Narrow surveillance beam $\Rightarrow$ replace the horn antenna with the wide beam helical antenna for broad surveillance angle
- 5 sec @ 7.49 km/s, range of 980 km: $2\arctan\left(\frac{7.49\times2.5}{980}\right)\simeq 2.2^\circ \ll$ horn antenna beamwidth ($16-18^\circ$ @ 20 dB gain) $\Rightarrow$ helical or horn antenna towards the satellite (better reference channel quality)



Distance from reference to surveillance antenna: 15 m $\Rightarrow$ excessive losses of RG-58 (>30 dB), use LMR-400 (≤ 6 dB) losses at 5.4 GHz.

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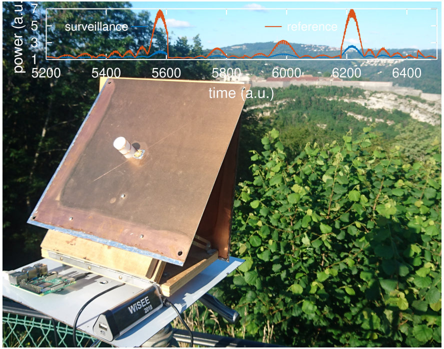
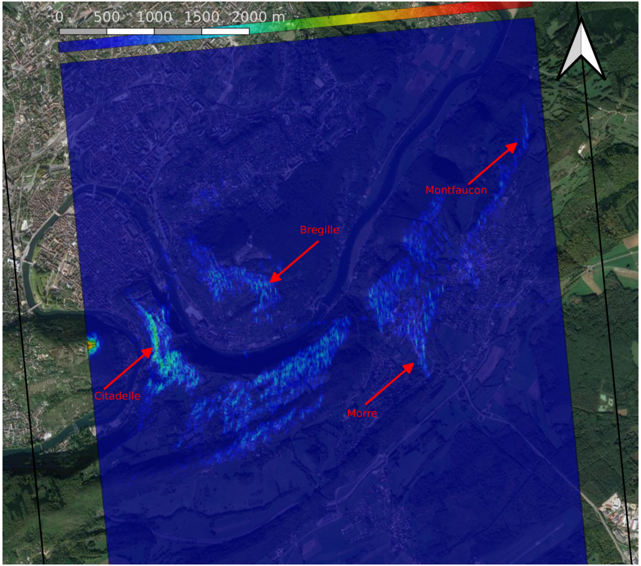
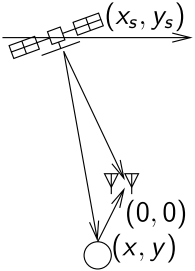


- no need for accurate satellite position computation: only satellite velocity is needed with pulse repetition interval
- assumption that satellite-target distance $\gg$ target-receiver distance
- accurate scale and positioning of reflectors over aerial image $\longrightarrow$



Why inverse Fourier transform for azimuth compression?

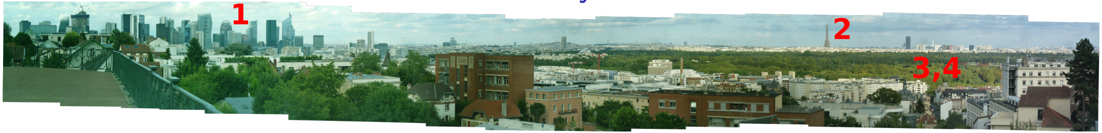
- **Range compression:** cross-correlate reference recorded chirp with surveillance using $FFT(xcorr(ref, sur)) = FFT(ref) \cdot FFT^*(sur)$
- **Azimuth compression:** it is known [8] that if a signal is $\exp(j2\pi k_x \cdot x)\exp(j2\pi k_y \cdot y)$ then its Fourier transorm is a Dirac function at (x, y): k_x and k_y are the dual quantities to x and y
$\Rightarrow$ can the recorded matrix $(sample(t), satellite\_position)$ be expressed under this shape?

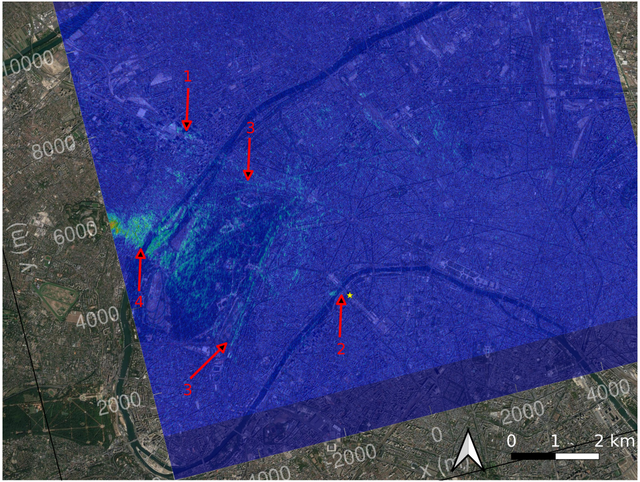


1. Satellite at (x_s, y_s) moving uniformly along x, receivers at $(0, 0)$, target at (x, y)
2. Satellite-receiver range: $R_1 = \sqrt{(x_s)^2 + (y_s)^2} \simeq y_s + \frac{1}{2}\frac{(x_s)^2}{y_s}$ since $y_s \gg x_s$ and the Taylor series $\sqrt{u^2 + v^2}$ with $u \ll v$ is $v\sqrt{1 + (u/v)^2} \simeq v\left(1 + \frac{1}{2}(u/v)^2\right) = v + u^2/(2v)$
3. Satellite-target range: $R_2 = \sqrt{(x_s - x)^2 + (y_s - y)^2} \simeq y_s - y + \frac{1}{2}\frac{(x_s - x)^2}{y_s - y} \simeq y_s - y + \frac{1}{2}\frac{(x_s - x)^2}{y_s}$
4. Target-receiver range: $R_3 = \sqrt{x^2 + y^2}$ independent on x_s
5. Phase: $\varphi = 2\pi f \tau = \frac{2\pi}{\lambda} R$ for narrowband signal, with $\tau = R/c$
6. Path difference $R_3 + R_2 - R_1 \Rightarrow$ phase difference: $2\pi f(\underbrace{R_3}_{\text{target range}}/c) + \frac{2\pi}{\lambda}(R_2 - R_1)$
$= 2\pi f R_3/c + \frac{2\pi}{\lambda}\left(-y + \frac{1}{2y_s}\underbrace{((x_s - x)^2 - (x_s)^2)}_{a^2 - b^2 = (a+b)\cdot(a-b)}\right) = \underbrace{2\pi f(R_3 - y)/c}_{\text{FFT in range}} + \frac{2\pi}{\lambda}\left(-\frac{x}{2y_s}(\underbrace{2x_s}_{\text{FFT in azimuth}} - \underbrace{x}_{\text{independent on } x_s})\right)$ which separates range and azimuth compression as a 2D iFFT following the appropriate variable translation along f and x_s

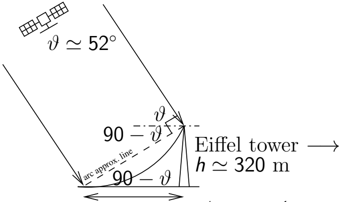
[8] https://hforsten.com/synthetic-aperture-radar-imaging.html

Paris dataset from Mont Valérien: "layover" effect on Eiffel tower





1: business district buildings ("La Défense")
2: Eiffel tower off by 400 m!
3: straight roads ("bois de Boulogne")
4: Seine river



x so that $h/x = \tan(90 - \vartheta)$
i.e. $x = h/\tan(38^\circ) = 409$ m

Top of tower appears closer since signal reaches receiver before bottom of tower

Remote sensing and SAR radar images processing – Physics of radar, p.40, ESA/CNES at https://earth.esa.int/c/document_library/get_file?folderId=226458&name=DLFE-2127.pdf

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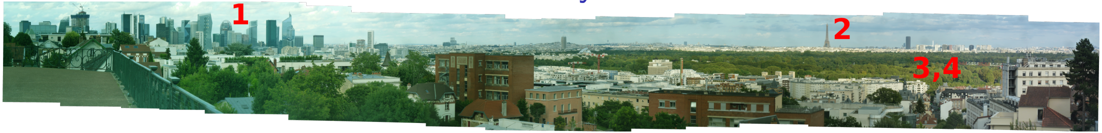

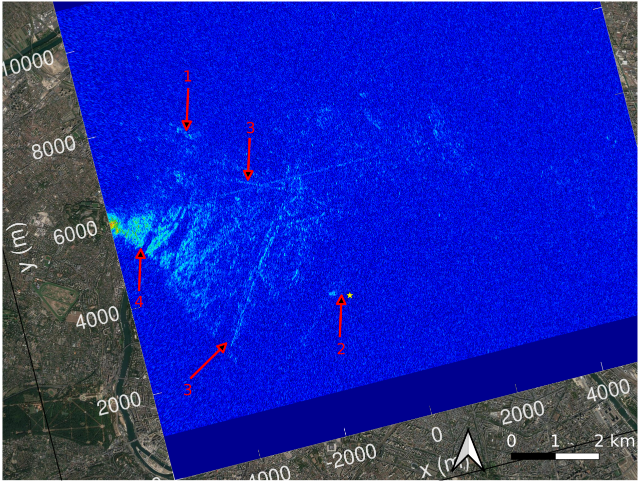

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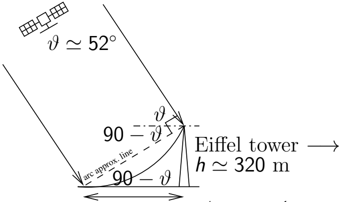

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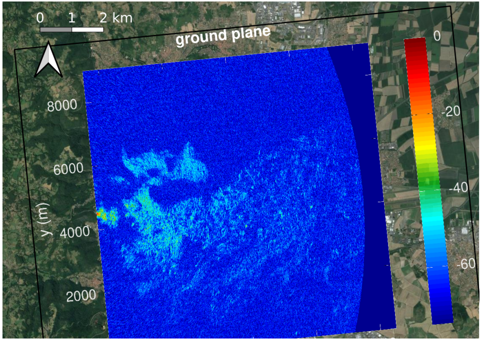
Conclusion

- "Low cost" educational opportunity for PBR measurement using moving source (B210 + RPi4 + homemade antenna) and fixed receiver
- real life implementation of "complex" processing algorithm and assess result quality
- advanced processing: 2D to 3D projection accounting for real geometry and achieving quantitative ground coordinates



↑ Portable system deployed in Clermont-Ferrand (center of France)

Github repository: `https://github.com/jmfriedt/sentinel1_pbr`

Perspectives: InSAR measurement by comparing phase of succesive measurements
UAV based acquisition system for better viewing angle (acquisition only lasts a few seconds)

Many more spaceborne RADARs to investigate: J. Rosen, *Shifting ground*, Science **371** (6532), pp. 876-880 (2021)

"Since 2018, the number of civil and commercial SAR satellites in orbit has more than doubled. And at least a dozen more are set to launch this year, which would bring the total to more than 60."