SAR introduction course

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Idea: get some hands-on experience with basic signal-processing methods for radar imaging. The course can also seen as a programming introduction course applied on radar data.

1 Exercise one: 1D data

This exercise provides an example how the range-compression (range-focusing) of a radar system works. Another keyword for the method is "matched pulse" filtering. (Frequency-step radars and frequency-modulated continous wave (FMCW) radars use a different approach.)

1.1 Visualization of a Chirped pulse

Plot real and imaginary components of a chirped puls $s(t)$ with the form

$$s(t) = \begin{cases} \exp\left(it \cdot [\omega_0 + \pi \beta_c t]\right) & |t| < \frac{\tau_p}{2} \\ 0 & \text{else} \end{cases} \tag{1}$$

The pulse envelope is rectangular; the envelope can also be called box-car. Where $\omega_0 = 2\pi f_0$ is the central frequency [s^{-1}], τ_p is the puls length [s] and β_c the frequency change rate [Hz/s]. The bandwidth of the pulse is given by $f_{bw} = \beta_c \cdot \tau_p$ [Hz].

1.1.1 zero padding

Plot pulse with some zeros padded

1.2 pulse compression by matched filtering

1.2.1 ...in time domain

Compress the pulse in time domain by a convolution with the filterfunction $h(t)$ and plot it. In principle you calculate the autocorrelation function $g_1(\tau)$ of the puls with itself:

$$g_1(\tau) = \int_{-\infty}^{+\infty} s^*(t) s(t+\tau) \mathrm{d}t = \int s(t') h(\tau - t') \mathrm{d}t' = (s * h)(\tau) \tag{2}$$

Where $t' = t + \tau$ and the matched filter function is defined as $h(t) = s^*(-t)$.
Literature: *Chapter 1-2.1.1 in the "Scientific SAR User's Guide" by Coert Olmsted.*
(IDL functions which may help: *conj, reverse, convol, findgen, complex, complexarr, fft, abs, plot, window, legend*)

1.2.2 ...in frequency-space

As the convolution is very computationally intense compress the pulse in frequency domain:

$$g_1(\tau) = \mathcal{F}^{-1}\Big\{\mathcal{F}\left((s * h)(\tau)\right)\Big\} = \mathcal{F}^{-1}\Big\{\tilde{s}(\omega)) \cdot \tilde{h}(\omega)\Big\} \tag{3}$$

Literature: *Chapter 2.1.2 in the "Scientific SAR User's Guide" by Coert Olmsted.*

1.3 Hamming Window

The hamming window is used to reduce side lobes. See e.g. Wikipedia.

1.3.1 ...in time domain

Use a hamming window ($\alpha = 0.54$) to weighten the sharp edges of the pulse in time domain and compare the the compressed pulse (and the side-lobes) with the one from section 1.2.1

$$w(t) = (\alpha - 1) \cdot \cos(\frac{2\pi t}{t_p}) + \alpha \tag{4}$$

1.3.2 ...in frequency domain

Use a hamming window to smooth the sharp edges of the frequency spectrum and comment on the compressed pulse. The result is not exactly the same as weighting in time-dimain, because the approximation

$$(h * w)(\omega) \approx h(\omega) \cdot w(\omega - \omega_0) \tag{5}$$

is used. For a hamming window in frequency space use the following weighting function

$$w(t) = (\alpha - 1) \cdot \cos(\frac{\omega - \omega_0}{f_{\text{bw}}}). \tag{6}$$

1.4 Multilooking

Multilooking is basically a spatial smoothing filter which is used to reduce the effect of "speckle" in radar images. This can be a simple spatial box-car filter, or different parts of the spectrum can be focused separately the resulting image intensities are averaged. Multilooking can also be done over a time-series of many images which can be used to enhance the resolution compared to a single radar image.

Speckle are an effect of the coherent illumination used in radar imaging. The same speckle effect appears when a laser is used to illuminate a rough surface. Incoherent light (from thermal radiation sources) does not show the effect of speckle because of the short coherence time of light. The long ”exposure” of a light-illuminated scene (Photo, Eye) of a few milliseconds average already over many many coherent representations of the extremely quickly changing speckle pattern. However, a radar uses a strictly defined pulse shape which does not changes during imaging; therefore speckle remain visible in the radar scene.

1.4.1 ...in time

split the signal in two parts:

$$s_1(t) = s(t) \qquad \forall \quad t < 0 \tag{7}$$
$$s_2(t) = s(t) \qquad \forall \quad t \geq 0 \tag{8}$$

compress each signal using a matched filter and average the absolute values of the signal (the intensity envelopes). Plot the absolute value of the compressed pulse.

1.4.2 ...in frequency

split the spectrum of the signal in two parts:

$$s_1(\omega) = s(\omega) \qquad \forall \quad \omega < \omega_0 \tag{9}$$
$$s_2(\omega) = s(\omega) \qquad \forall \quad \omega \geq \omega_0 \tag{10}$$

compress each signal in frequency domain, transform back to time domain, and average/add the envelopes (absolute values) of the compressed pulses.

2 Exercise two: 2D data

A radar image represents two-dimensional data. This requires not only focusing in range (see first exercise) but also focusing in azimuth (= along track, i.e. in the flight direction of the sensor).

You will find the formulas required for the range and azimuth chirp rates in the tutorial on epsilon nought (http://epsilon.nought.de/).

2.1 2D Chirp (point source)

Use the information in the file *chirp_2d_test_constants.txt* and *chirp_2d_test.dat* to focus (or compress) the 2-D radar raw data. The image represent the raw-format of radar data of a single strong scatterer. After focusing in range an azimuth, the image still consists of complex values. This data format is called single-look-complex or SLC. Most radar data is distributed in the SLC format.

Definition of the .DAT format: two LONG values representing the number of pixels in range and azimuth direction. Then follows a sequence of complex values which represent a 2D matrix of the dimension given by range and azimuth. Write a binary-reader function to import the data. When you visualize the data, you should see several rings. (IDL functions that may help: openr, readu, close, free_lun, lonarr, complexarr, shade_surf)

2.1.1 compress the 2D raw data

Plot intensity and phase of the compressed image.

2.1.2 compress the 2D raw data using an Hamming filter in azimuth

Visualize the intensity and phase of the compressed image.

2.1.3 compress the 2D raw data using two looks in the azimuth spectrum

Split the azimuth-spectrum and focus both spectra independently. Then average the magnitude of both images. Literature: *Chapter 2.2 in the "Scientific SAR User's Guide" by Coert Olmsted.*

2.2 2D image from raw format

Use the information in the file *ers_constants.txt* and the radar raw data *ers_raw_demo.dat* to focus (or compress) the radar raw-data in the 2D chirp image. Note, that the image is negatively chirped ($Bw = -1.55404d7$)

- Visualize the data after range compression
- Visualize the data after azimuth compression

- Visualize the data after azimuth compression with Hamming in azimuth

Hint: you can apply a spatial smoothing filter (boxcar, gauss, etc.) on the image intensity to remove the strong image speckle. This reduces the resolution but improves the radiometric accuracy of homogeneous areas.

2.3 Image interpretation

Interpret the image. What can you see? (tip: you might want to scale the amplitudes after applying the Hamming filter to conserve the overall power) (IDL functions that may help: tv, bytscl, congrid, hanning)
Literature: *Chapter 3.1 in the "Scientific SAR User's Guide" by Coert Olmsted.*

2.4 2D image from range compressed format

Use the information in the file *rdemo040689_cmp_constants.txt* and *rdemo040689_cmp.dat* to focus (or compress) the 2D raw data. Note, that the data is already compressed in range.

- Plot data after azimuth compression (The data is ALREADY range compressed)
- Plot data after azimuth compression AND applying a Hamming-window on the azimuth spectrum.

3 Exercise three: InSAR: Interferometry

Radar interferometry usually contains the following processing steps: precise coregistration (with sub-pixel accuracy) of two radar images in the single-look-complex format (usually done based on the image intensity. "Spectral diversity" is another method). After coregistration an interferogram is formed. The phase if the interferogram contains information about surface deformation and topography (with some phase contribution from the atmosphere) and the coherence is a measure how reliable individual phase values are. Usually, one subtracts a known phase from the interferogram and analyses only the residual phase with respect to the reference. The know phase usually represents a rough estimate (as precise as possible) of the topography. In this exercise this estimate is so rough that the earth is assumed to be flat and that the radar incidence angle does not vary across the scene. For a flat earth, the remaining phase (after subtracting the flat-earth-phase) corresponds to the topography. Each phase cycle represents a certain height step. On says the height-of-ambiguity $HoA = 100$m when one phase cycle of 2π corresponds to a height of 100 meters.

The coherence, which is basically the correlation coefficient between two SLC images, can be affected by various contributions which cause a decorrelation of the radar images. This can be a bad signal-to-noise ratio (e.g. from low backscatter on water), temporal decorrelation (when the two images where acquired at different times), baseline decorrelation because the image spectra do not completely overlap.

3.1 COREG and FLAT EARTH PHASE

3.1.1 coregistration

Coregistration is done here only on the pixel-level and not with sub-pixel precision.

- Read-in the two .dat files.
- Perform 2-D cross-correlation to find range/azimuth shifts between image 1 and image 2. Use a simple amplitude cross correlation function. Hint: The cross correlation is most efficient when performed in frequency domain: Let $x(t)$ and $y(t)$ be two signals. The cross-correlation function is defined as

$$R_{xy}(\tau) = \int x(t) \cdot y^*(t+\tau)dt = \mathcal{F}^{-1}\left\{x(\nu) \cdot y^*(\nu)\right\} \tag{11}$$

- Shift image 2 so that it aligns with image 1.

3.2 phase correlation method

Implement the phase correlation method [1] and analyze the position of the peak of the 2D-cross correlation function with sub-pixel accuracy (can be done manually). Shift the image using an appropriate interpolation method (bilinear, sinc, fft).

3.3 Interferometric coherence

Calculate the complex valued coherence from the two coregistered SLC images. Use different filter windows (3x3...11x11). Plot magnitude and phase of the coherence.

3.3.1 Remove flat earth phase

Identify the dominant frequency component in the phase of the interferogram (of the coherence), i.e. identify the dominant fringe frequency. This can be done using an fft or just by counting fringes and determining their main direction. Generate a 2D-matrix which contains the flat-earth phase. Multiply the flat earth phase as an exponential $e^{-1\vec{k}_{\text{flat}}\cdot\vec{x}}$ with one of the SLC images to remove the flat-earth phase before calculating the coherence. How and where does the coherence change when applying the flat-earth removal?

3.4 common range-spectrum filtering

comment: This is a very advanced interferometric processing step and might not be too important for now.

- Perform common range-spectrum filtering on the two coregistered images from 3.1.1. (According to [3], [2]): First determine the wave-number shift between the two images based on the fringe-frequency of the interferogram where the flat earth phase has not yet been removed. Then remove the Hamming-filter from the range-spectra of both images. Apply two new Hamming-like filter functions which are shifted against each other corresponding to the wave-number shift of the two images (this preserves only overlapping bandwidth of the two images, called master and slave). Then refocus the two images and calculate the interferogram.
- Display histograms of coherences BEFORE and AFTER range filtering.
- Does the resolution of the images change?

References

[1] Image registration methods: a survey, Zitova, B, and Flusser, J., Image and Vision Computing, 2003, p.977-1000, vol 21.

[2] Zebker, H.A. and Villasenor, J., Decorrelation in interferometric radar echoes, 1992, vol. 30, no. 5, p.950-959, 10.1109/36.175330

[3] Gatelli, F. and Guamieri, A.M. and Parizzi, F. and Pasquali, P. and Prati, C. and Rocca, F., The wavenumber shift in SAR interferometry, 1994, vol. 32, no. 4, p.855 -865, 10.1109/36.298013,

4 Exercise four: Polarimetry

Data set: Alling data set of 2000

1. Visualize power (absolute-squared) of [S]-Matrix Elements (Shh, Svv, Sxx) in dB (coloured). Take care: σ_0=Power of S-matrix-element*(sin(incidence))/1000000. dB = $10 \cdot \log_{10}(Power[W]/1\,\mathrm{W})$ Plus calculate the histograms for everything.

2. Calculate polarimetric coherences (HH-VV, HH-XX, VV-XX, LL-RR) and visualize the absolute and the phase of the coherence in black and white. Plus calculate the histograms for everything.

3. Calculate the Covariance Matrix [C] and visualize the elements C1, C22, C33 as powers and the elements C13, C23, C12 as powers and their phases. Plus calculate the histograms for everything. ([1], chap. 3ff, 3.2).

4. Calculate the Coherency Matrix [T] and visualize the elements T11, T22, T33 as powers and the elements T13, T23, T12 as powers and their phases. Plus calculate the histograms for everything. ([1], chap. 3ff, 3.3).

5. Calculate the Total power (=span = Froboenius norm = Tr(SS^*), [1],chap. 3.2.2) of the [S]-, the [T]- and the [C]-matrix, visualize the images and plot all three histograms in one plot. What is the outcome? ([1], chap. 3ff.).

6. Calculate the eigenvalues and eigenvectors of the [T]-matrix in an analytical way ([1], appendix A.6) and with the built-in IDL routine 'LA_Eigenql'. Compare both solutions. Differences between the solutions? Visualize the eigenvalues and compute the histograms? Do you notice anything, if you compare them?

7. Calculate the entropy (H), alpha angle (alpha), dominant alpha angle (alpha from dominant eigenvalue=alpha1) and anisotropy (A), Visualize in colour and plot the histograms. ([1], chap 7.).

8. Visualize entropy-alpha in a 2D-histogram plot and compare with the classification published in [3] and [1] (chap. 7.8). Plus visualize H-A in a 2D-histogram plot.

9. Calculate a model-based decomposition (Freeman-Durden) on the [T]-matrix using [4], calculate the powers and visualize the powers. Is there a problem with this decomposition?

References

[1] Book: Polarimetric RADAR imaging: From basics to applications (Lee, Pottier) - chapter 2-3 and chapter 6-7

[2] Paper: A review of target decomposition theorems in RADAR polarimetry (Cloude & Pottier)

[3] Paper: An entropy based classification scheme for land applications of polarimetric SAR (Cloude & Pottier)

[4] Paper: A Four-Component Decomposition of PolSAR images based on the coherency matrix (Yamaguchi & Yajima & Yamada)

5 Exercise five: PolInSAR

The aim of the exercise is to understand how the random-volume over ground model works by determination of the forest height according to the 3 stage inversion by Cloude and Papathanassiou [1]. Data: sim_rvog_data.zip. This requires the following steps:

1. read the complex data. Plot amplitudes. Compute and plot coherence magnitudes and coherence phases for baseline 12 and baseline 13 (i.e. baseline12 = image 1 and image 2).

2. calculation of the Pauli components.

3. flat earth correction: Compute flat-earth phase analytically using the given constants and remove from slave pass. i.e. Determine geometric phase difference between pass 1 and pass 2 and pass 1 and pass 3 assuming flat topography.

4. calculation of hh,vv, xx, pauli1 (HH+VV) and pauli2 (HH-VV) coherences.

5. plot magnitude and phase of coherence for hh, vv, xx (both baselines) in a 2D-plot.

6. compare in a histogram the magnitude of the coherence of hh, vv and xx (both baselines).

7. plot magnitude and phase of coherence for the five datasets hh, vv, xx, pauli1 and pauli2 (baseline 12) in the unit circle.

8. start 3-stage Pol-InSAR inversion for topographic phase, extinction, and tree height: Make a line fit (Linear fit to coherences. Plot complex unit circle and locations of 5 coherence points. Fit line through the points.) HINT: use IDL LINFIT routine. To avoid infinite slopes one can also try shifting the points 90 degs. and re-compute LINFIT. Take the solution with the lowest CHISQ error.

9. find intersection(s) between best-fit line and the unit circle and project the points onto the line. HINT: use math! equation of a line and equation of a circle gives 2 eqns and two unknowns (coordinates of point of intersection)

10. determine the ground phase. HINT: Find Euclidean distance from each coherence to each of the two possible ground points. Determine where the XX coherence (typically has a smaller ground contribution than the other coherences) lies in relation to the other coherences (= intersection point of line with circle that is further away from xx coherence).

11. determine the ground phase (see 8 to 10) and show the ground phases of all points in a histogram.

12. create and plot lookup table (LUT) for coherence of vegetation: Assume XX coherence (projected to best-fit line) has no ground contribution. Perform integral from eqn. 8 (Cloude & Papathanassiou 2003). Compute 2D LUT (look-up table)

with different values of extinction (eg. vary from 0 to 2 dB/m) and height (eg. vary from 0 to 30 m or up to interferometry sensitivity height h_π).

13. calculate vegetation height and sigma (extinction) by the Look-up-table.

14. plot vegetation height histogram and 3D-plot (shade surf or contour).

Please ask for help, if you are not advancing after half a day. You are not alone in this adventure.

H	= 3e3	(m)	sensor height
lambda	= 0.24	(m)	wavelength, L-band
B_{12}	= -10	(m)	horizontal baseline btween image 1 & 2
B_{13}	= -20	(m)	horizontal baseline between Image 1 & 3
W	= 100e6]	(Hz)	bandwidth in range
grng_res	= 0.5	(m)	ground range pixel spacing
θ_0	= 45	(°)	angle of incidence to image centre, assume constant for small area
c	= 3e8	(m/s)	speed of light
R_m	$= H/\cos\theta_0$	(m)	broadside range
α	= 0	(°)	local slope

Table 1: Constants for the calculation and of sim_data_rvog

Hint: The data given are modelled. The input parameters are:
topographic phase = 0.0
extinction = 0. 1 dB/m
height = 10 m

References

[1] Cloude & Papathanassiou ”Three-stage inversion process for polarimetric SAR interferometry”, 2003.

[2] Cloude & Papathanassiou ”Polarimetric SAR Interferometry”,1998.

[3] Papathanassiou & Cloude ”Single-Baseline Polarimetric SAR Interferometry”, 2001.