Getting more from the laser echo waveform

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2. Workshop "Alpine Airborne Hydro Mapping", 2016-02-11[1]

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System response and backscatter cross section

$$p_r(t) = \int_{-\infty}^{+\infty} h(t-\tau) \int_{-\infty}^{+\infty} p(\tau - \frac{2r}{v_g})\sigma(r)\,dr\,d\tau \qquad (1)$$

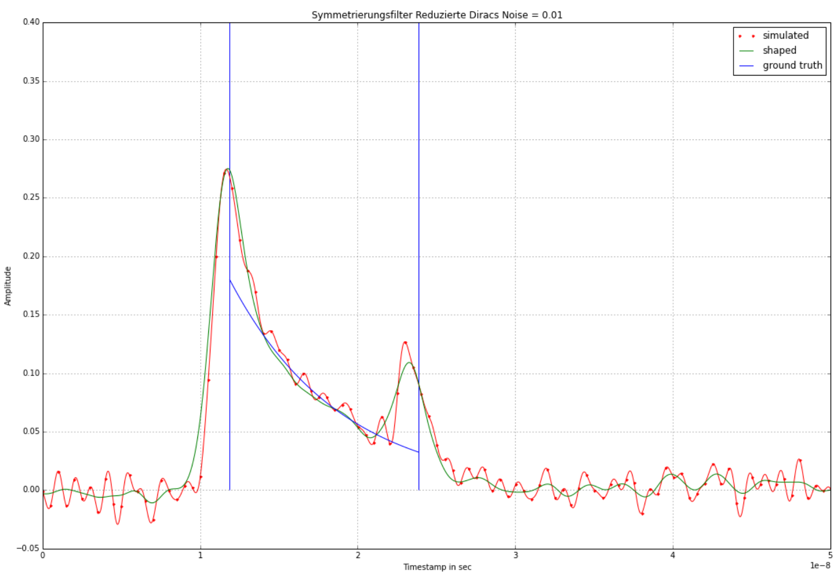
$$p_r(t) = \int_{-\infty}^{+\infty} s(t - \frac{2r}{v_g})\sigma(r)\,dr \qquad (2)$$

- Known: system response $s(t)$
- Measured: receive signal $p_r(t)$
- Sought: differential backscatter cross section $\sigma(r)$

$h(t)$ ... detector response, $p(t)$ ...outgoing pulse

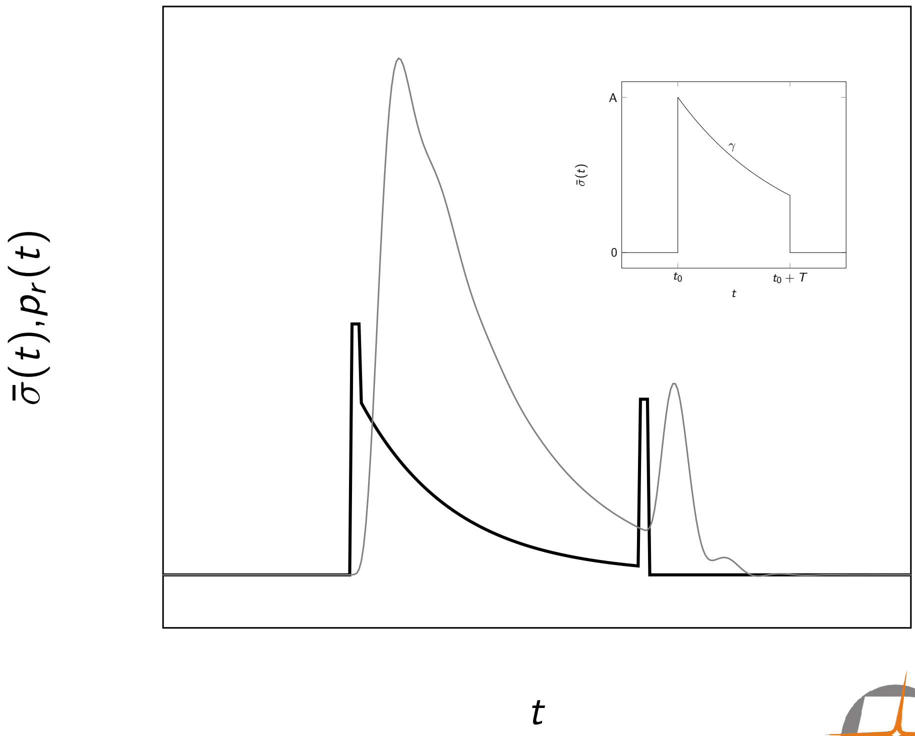
Parameterless or model?

Parameterless: deconvolution with shaping filter



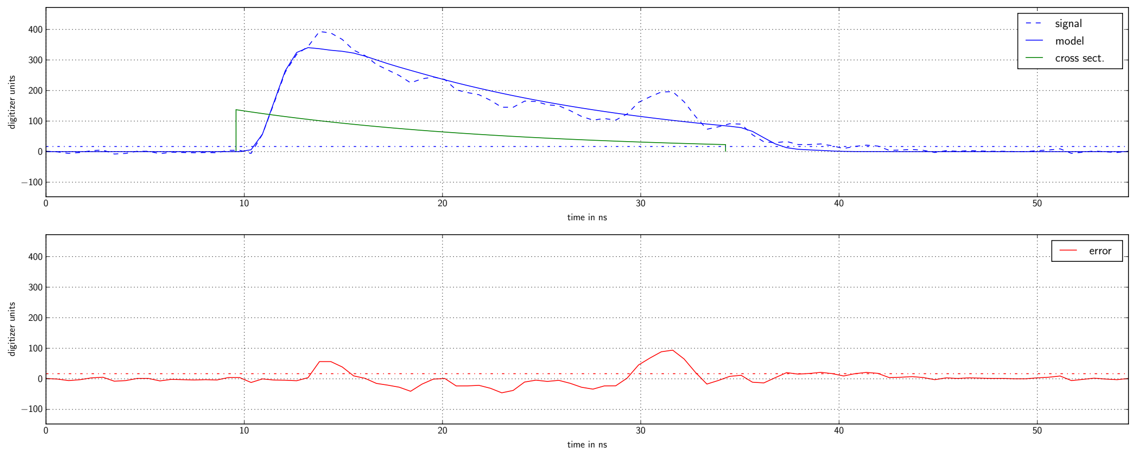
Parameterless or model?

Model: chaining of exponential segments



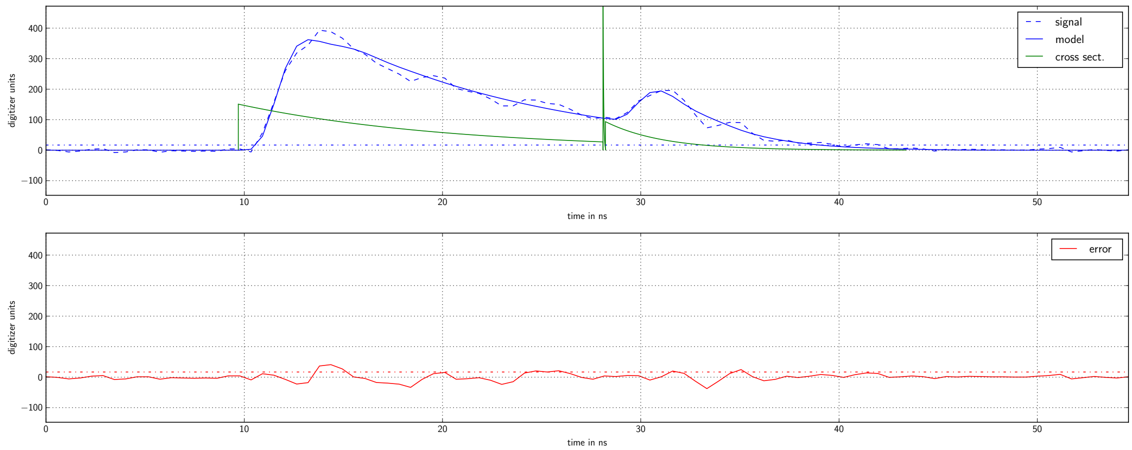
Exponential decomposition

Direct fitting of the exponential model



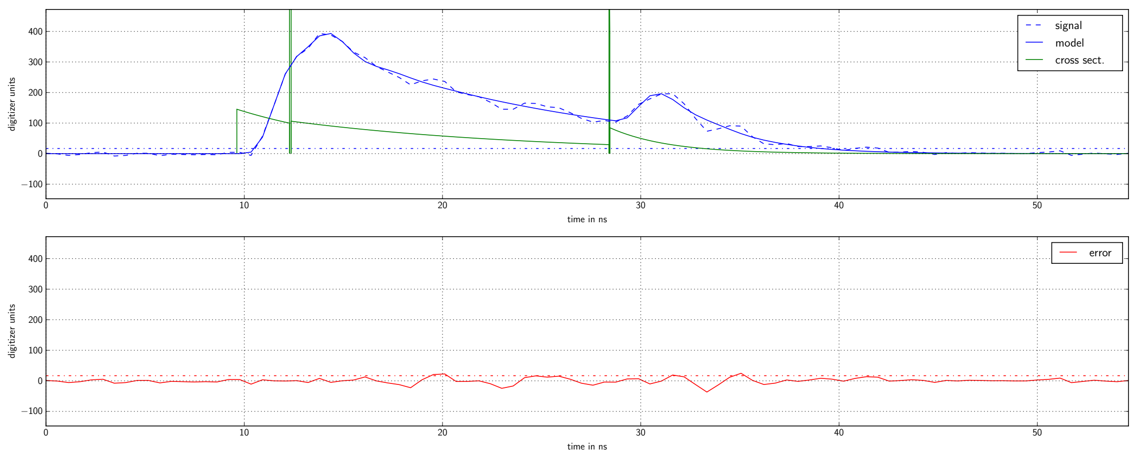
Exponential decomposition

Direct fitting of the exponential model



Exponential decomposition

Direct fitting of the exponential model



Water surface, ground and water column

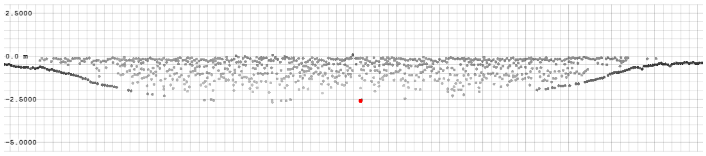


Image: online method

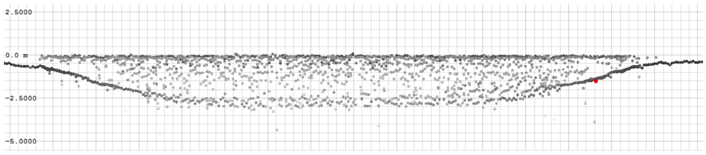


Image: online and exponential decomposition

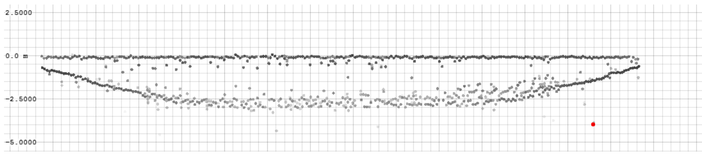


Image: exponential decomposition

RIEGL

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1 System response and backscatter cross section

The primary result of a (mono-static) radar measurement is a set of discrete ranges. This is done by evaluating the transit times an electro magnetic wave needs to travel from the source to scatterers and back, also known as the method of time of flight (TOF).

The time of flight method when used with pulse shaped waves has the property that echoes returned from solid flat targets exhibit the same shape as the outgoing wave, which makes it easy do measure round trip times accurately.

For targets, composed of several parts, the back traveling wave is the superposition of the echoes from the parts. This follows from the validity of the superposition principle for electromagnetic waves. In case the mutual distances of the target parts are larger than the spatial extent of the wave, it is easy to evaluate all distances since they are well separated.

When the inter-part distances are getting smaller the echoes start to overlap. Mathematically this can be expressed by a so called convolution integral between the differential backscatter cross section (DBCS) of the target constellation and the radar pulse.

The so convolved optical pulse reaches the detector. In the general case the detector is an electronic device that posses memory and exhibits non linear behavior. For small signal amplitudes however the detector can be modeled as a linear time invariant (LTI) system, i.e. it can be mathematically described by a convolution integral. This means that the output from the detector can be seen as a chain of convolutions first between the DBCS and the pulse, followed by a convolution with the detector system.

Since for chaining of convolution operations the associative law is valid, it is possible to convolve the detector with the pulse first. The result is termed the system waveform since, for simplicity, it is dependent on instrument parameters only. The received signal finally can be described with a single convolution between the DBCS and the system waveform.

2 Modeling or parameterless?

Recovering the DBCS resp. the target structure requires inverting the convolution. This operation is called deconvolution and is well described in the literature. Unfortunately, if measurement noise is present, meaning practically always, the inversion can be performed only in an approximative way.

From linear system theory it is a well known result, that a convolution with a pulse shaped function results in a smearing of the input function. Vividly this can be understood as a low-pass filter operation on the input signal. High frequency parts of the signal are getting very small to the degree that they are practically vanishing. Deconvolution seen in this context can then be understood as the desire to construct a filter that amplifies the high frequency parts in an attempt to invert the damping of the high frequencies.

Unfortunately the high frequent parts of the received signal are in the same order of magnitude than the measurement noise, if not even smaller. A "perfect" filter, a filter that would be able to invert a noise free received signal, will fail badly with noise present, since it will amplify not only the very small high frequent parts of the signal but also the noise. Such a filter fails to the degree of plain unusable.

A practical implementation of a deconvolution filter avoids to amplify the noise while sacrifying the perfect reconstruction property. The result is a signal, with dependencies on measurement instrument parameters removed as much as possible.

For several reasons the desired result of a radar measurement is a discrete range, possibly enhanced by a classification of the target point. Consequently the deconvolved signal needs to be converted into a discrete number of target ranges. Our point here is, that this step assumes a certain model of the target, e.g. the simple presumption of an ensemble of discrete scatterers.

So finding and identification of appropriate models is not only important in the engineering practice, but more so it is for understanding nature in general. So e.g. a better model of a target configuration such as the water body could be described as a chain of exponentially damped segments.

3 Exponential decomposition

We at company Riegl have developed a method to decompose the signal that is back scattered from a water body, into a sequence of exponentially damped segments.

The algorithm is based on a method for the representation of the system waveform as a sum of complex exponentials, patented by company Riegl. This expression of the system waveform allows for an explicit evaluation of the convolution integral and results in an analytic model of the received waveform which can be evaluated efficiently.

First a single exponential segment, with four parameters, the range, the peak value, the exponential decay and depth, is fitted to the peak of the absolute maximum. The resulting model is subtracted from the measured data and the remaining error is treated as a new set of data.

The following step again models the maximum peak by another set of exponential parameters. The model described by the entire set of found parameters is again subtracted from the original data.

This process is repeated until some error criterion, one of which is the squared sum of differences, is sufficiently small.

4 Water surface, ground and water column

Part of the potential of the method of exponential decomposition can be shown by reference to measurements of the water body. The shown example has been extracted from a measuring campaign with Riegl's VQ 880-G. This instrument has been specifically equipped with a green 532 nm laser for hydro-graphic applications.

All measurement points are intensity coded by their amplitude. A dark point corresponds to a strong, a light one to a weak signal amplitude.

The first picture shows points that have been acquired by the real time algorithm of the instrument. The exponential decaying slope of the signal adds to the always present noise eventually exceeding the detection threshold and resulting of an increased number of targets detected below the water surface. In the example shown this even reduces the instruments capability to recognize the bottom of the water body.

The second picture shows the overlay of points acquired with the on-line method and the exponential decomposition. Besides the darker appearance of points near the surface one can also see a higher detection probability of points from the ground.

Eventually the third picture is made of points solely acquired by exponential decomposition of the recorded waveform. One can readily see the clustering of data points near the boundary layers.

Although a detailed evaluation of the remaining parameters of the exponential decomposition, such as decay and width, has been performed it may be expected that it should be possible to make use of them e.g. for the automatic classification of water bodies.