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COMPUTER MODELING OF A LIDAR RECEIVING SYSTEM WITH A NANOSECOND RESOLUTION

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INTRODUCTION

Lidar systems of nano- and subnanosecond resolution will be capable to probe remotely the small-scale backscattering of different media (atmosphere, subsurface waters, turbulence etc). The creation of such systems is restricted mainly by the lack of proper receiving methods, combining the both high temporal and amplitude resolution, good sensitivity, short integration time, wide dynamic range. The goal of this work is to model numerically a new photodetection technique by solving an inverse problem, developed in [1-3], for use in the high-resolution lidar systems. The effects of the system instabilities on the accuracy of retrieved lidar profiles are investigated.

BLOCK-SCHEME OF THE LIDAR RECEIVER

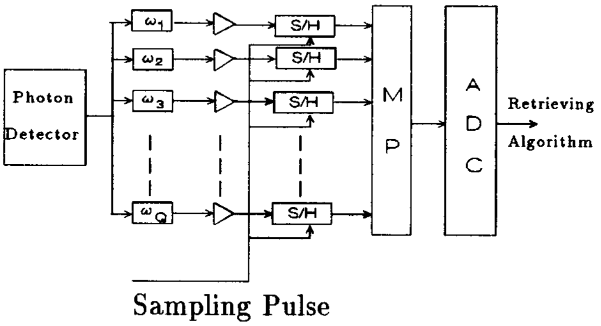

Figure 1: Block-scheme of the lidar receiver.

The block-scheme is shown in Fig.1. The gated photon detector PD (photo-multiplier tube (PMT) or photodiode-amplifier) is fed to a number of resonators with frequencies $\{\omega_q\}$ and decay factors $\{\beta_q\}$, $q = 1 \dots Q$. The gated lidar return (Fig.2b) within some gating interval T_s excites decayed oscillations into the resonators [1,2]. After the amplification they are sampled in some instant $T_m \gg T_s$ by sample/hold (S/H) schemes. Through a multiplexer MP they are digitized by a low-speed, high-amplitude-resolution analog-to-digital converter (ADC). Using the algorithm, given below, a lidar profile with an enhanced resolution $\Delta\vartheta$ can be retrieved (Fig.2d). By scanning the gating delay T_d from pulse to pulse, the entire lidar profile may be recorded.

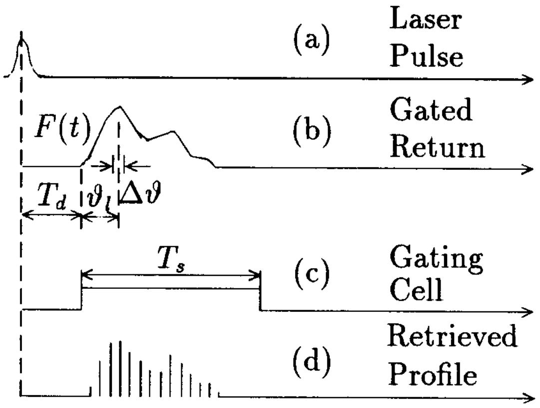

Figure 2: Timing diagram.

INVERSE PROBLEM FOR RETRIEVING THE LIDAR PROFILE

The excitation of a resonant system by an external force $F(t)$ at a zero initial conditions in the instant T_m is given by [4]

$$(1)\quad b_q(T_m) = A_q \exp(-\beta_q T_m) \times \int_0^{T_m} F(t) \exp(\beta_q t) \sin\left[\omega_q (T_m - t)\right] dt,$$

where A_q is a constant, $F(t)$ is the PD output voltage (the gated lidar profile). If the resonators are fed directly to the PMT-anode then $F(t)$ is given by $F(t) = \sum_{k=1}^{G(t)} h(t - t_k)$, where t_k is the k-th-electron arriving-time and $G(t)$ is the total number of electrons. The following linear set of equations with respect to the lidar data could be written [1,2]

$$(2)\quad b_q(T_m) = \sum_{l=1}^{L} \alpha_{ql} F(\vartheta_l),$$

where

$$(3)\quad \alpha_{ql} = A_q \exp(-\beta_q T_m) \times \int_{T_d+\vartheta_l-\Delta\vartheta/2}^{T_d+\vartheta_l+\Delta\vartheta/2} \exp(\beta_q t) \sin\left[\omega_q (T_m - t)\right] dt,$$

In Eqs.(2) and (3) $\vartheta_l = l\Delta\vartheta$ is the internal delay, $\Delta\vartheta = T_s/L$ is the temporal resolution, $l = 1 \ldots L (L = Q$ for amplitude detection). The resonator frequencies could be chosen as a multiple to $2\pi/T_s$ (i.e. as Fourier frequencies). This case was analyzed in details in [2]. The maximum frequency ω_Q is limited by the PD bandwidth, which may be $\gtrsim$ 1 GHz. Using the surface-acoustic-waves (SAW) resonators with frequencies up to 1 GHz, a resolution of the order of 1ns could be obtained by a low speed ADC at a high dynamic range. Because of the use of temporally-limited eigen-functions of the form $\exp(-\beta_q - j\omega_q)t$, the system formed by Eqs.(2) is not a true Fourier-one, but its matrix is well conditioned at higher L.

COMPUTER MODEL

In order to analyze the receiver performance a computer model of the entire measurement and calculation process was developed. The measurement of the output resonator signals is modeled by solving the wave equations

$$(4) \quad L_q\ddot{b}_q(t) + R_q\dot{b}_q(t) + b_q(t)/c_q = F(t)$$

for the set of frequencies $\{\omega_q\}$ at an external force $F(t)$; L_q, R_q, and c_q are the equivalent inductance, resistance and capacitance, respectively. The solutions $b_q(T_m)$ play the role of a real experimental measurement, and are used in the left-hand side of Eqs.(2). The matrix coefficients $\{\alpha_{lq}\}$ are calculated using Eqs.(3). The final goal of this procedure is to retrieve the external force $F(t)$ with the resolution $\Delta\vartheta$.

The retrieving accuracy will be affected by noises. External noises in the lidar profile are usually dominating. They are assumed as a part of the input profile recorded by the receiver. In the following we will analyze the effect of internal receiver's instabilities on the retrieved lidar profile only. They may be described by the variation coefficient $C_v = \sigma_n/b(T_m)$, where σ_n is the total noise rms variation. There are two types of instabilities: amplifier- and sampling- noises. The effect of the amplifier noises may be essentially reduced by narrowing the amplifier bandwidth to the order of $(5 \div 10).2\pi\beta_q \ll \Delta\omega_s$, where $\Delta\omega_s$ is the signal bandwidth. The sampling noises are of the order of the ADC resolution. Using S/H schemes and a low-speed high-amplitude-resolution ADC ($10 \div 16$ bits/$1 \div 10$ MHz) the realistic values of the total uncertainties will be of the order of $C_v \sim 0.01 \div 0.001$. The resonator uncertainties are estimated in the computer model by including random relative variations $\delta\omega_q/\omega_q$ and $\delta\beta_q/\beta_q$ of frequencies and decay factors at the calculation of the matrix coefficients. The temporal sampling jitter of instants T_m is described by its rms variance δT_m.

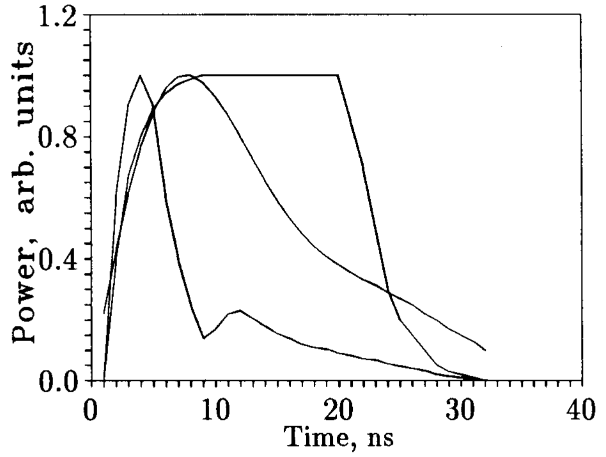

Figure 3: Models of lidar returns used in the simulations.

The uncertainties cause the increased retrieving instabilities if the matrix $\{\alpha_{lq}\}$ is not so well conditioned. In order to estimate the retrieving accuracy two joint parameters have been simultaneously accounted for – the cross-correlation coefficient R of the input and the retrieved lidar return and the lidar-signal area P (proportional to the signal energy) within the gating cell. The best performance of the receiving system corresponds to $R = 1$ and $P_{\text{input}} = P_{\text{retrieved}}$.

ANALYSIS OF THE ACCURACY AT RETRIEVING THE LIDAR PROFILES

The realistic number of resonators Q does not exceed 32. Three shapes of lidar returns have been used in our analysis (Fig.3). In the simulations the highest frequency was chosen $\omega_Q \approx$ 1 GHz at $Q_r = 100$ and therefore a resolution will be equal to 1 ns at 32 ns gating interval.

The cross-correlation coefficient R between the input and the retrieved return as a function of the relative instabilities C_v within the range $C_v = 0 \div 0.4$ is shown in Fig.4. For typical values of $C_v \sim 0.001 \div 0.1$ the value of $R \sim 1$ as well as the pulse area $P_{\text{input}} \approx P_{\text{retrieved}}$. Therefore, the quality of the retrieved profiles is very good. At high-

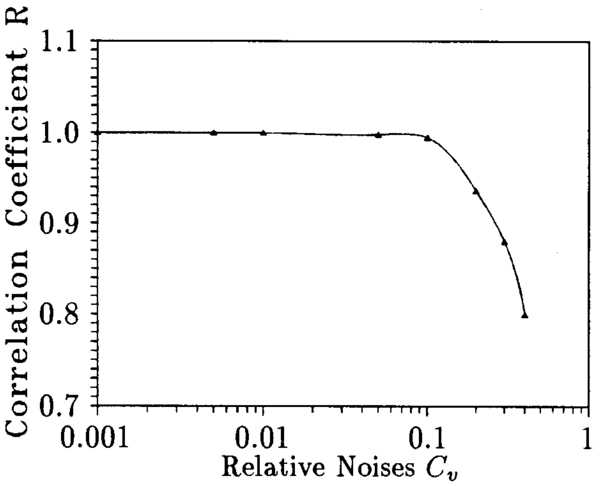

Figure 4: Correlation coefficient R as a function of the variation coefficient of internal noises C_v.

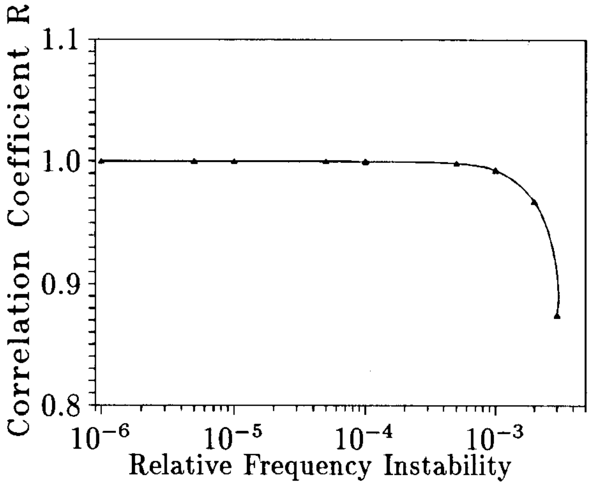

Figure 5: Correlation coefficient R versus the relative frequency instability.

er instability with $C_v \sim 0.4$ the value of R decreases to 0.8.

The coefficient R as a function of the relative frequency instability is shown in Fig.5. As seen, $R \sim 1$ up to $\delta\omega_q/\omega_q = 10^{-3}$. We found also, that the stability of the retrieving procedure does not depend significantly on the decay-factor uncertainties (up to $\delta\beta_q/\beta_q \lesssim 0.1$). These results show, that banks of SAW - resonators with a quality factor $Q_r \sim 20 \div 100$ may be successfully used for the creation of the system analyzed. Their very good frequency stability (10^{-5}) [5] will satisfy the above requirements.

The effect of temporal jitter is shown in Fig.6. The cross-correlation coefficient R remains ~ 1 at $\delta T_m \lesssim 10^{-3}$ or frequency-stabilized sampling sources and low-jitter S/H schemes are required to ensure the tolerable performance.

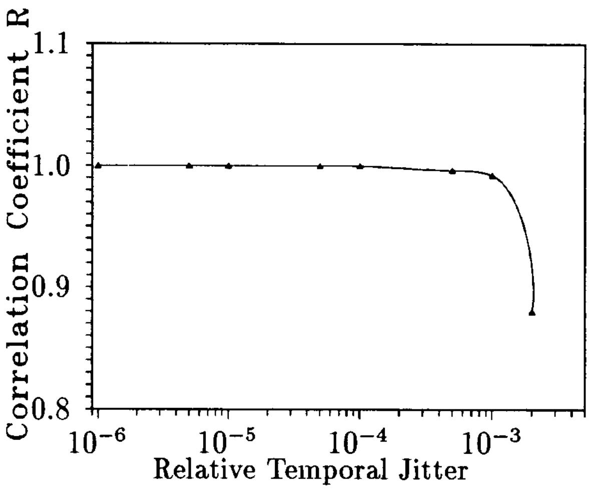

Figure 6: Correlation coefficient R versus relative temporal jitter.

CONCLUSIONS

A computer model of a photodetecting system for use in the high-resolution lidars ($\sim$ 1 ns) is developed by solving an inverse problem. It is shown, that the tolerable retrieving accuracy may be achieved at relative internal noises $C_v \lesssim 0.1$, frequency instability $\delta\omega_q/\omega_q \lesssim 10^{-3} \div 10^{-4}$ and relative sampling jitter $\delta T_m/T_m \lesssim 10^{-3}$. Such requirements may be satisfied using banks of SAW-resonators and frequency stabilized sampling sources.

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