Methods for Optical noise rejection in an Amplitude-Modulated Laser Optical Radars for Underwater Three-Dimensional Imaging

Amplitude-modulated (AM) laser imaging is a promising technology for the production of accurate three-dimensional (3D) images of submerged scenes. The main challenge is that radiation scattered off water gives rise to a disturbing signal (optical noise) that degrades more and more the quality of 3D images due to increasing turbidity. In our laboratory we have investigated several methods, both theoretically and experimentally, to suppress or at least reduce this contribution. These methods range from modulation/demodulation to polarimetry. In order to assess their effectiveness we carried out a series of experiments by using the laboratory prototype of an AM 3D imager. The laboratory is based on a laser at wavelength (λ = 405 nm), for marine archaeology surveys, in course of realization at the ENEA Artificial Vision Laboratory (Frascati, Rome). The obtained results confirm the validity of the proposed methods for optical noise rejection

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Metodi per la riduzione del rumore ottico in radar ottici modulati in ampiezza nell'*imaging* tridimensionale in ambiente sottomarino

I sensori laser basati sul principio della modulazione di ampiezza (AM) appaiono una promettente tecnologia per la digitalizzazione tridimensionale (3D) di oggetti in ambiente sottomarino. Il principale processo fisico che limita l'efficienza di tali dispositivi è quello dello scattering della radiazione laser da parte delle particelle sospese in acqua e che tende a degradare la qualità delle immagini registrate in maniera sempre più severa man mano che la torbidità dell'acqua aumenta. Nel nostro laboratorio sono stati eseguiti degli studi teorici e sperimentali volti a dimostrare l'efficienza di diversi metodi atti a minimizzare tale contributo. In particolare sono stati investigati metodi basati sulla demodulazione del segnale ricevuto dal sensore e sulla polarimetria. Gli esperimenti sono stati portati avanti per mezzo di un dispositivo prototipale basato su di un laser alla lunghezza d'onda di 405 nm. I risultati ottenuti confermano la validità dei metodi proposti

Introduction

In recent years, the growing interest for underwater 3D imaging has stimulated the development of 3D optical imagers specifically designed to operate underwater[1]. Applications range from the monitoring of submarine archaeological sites to the inspection of submerged structures for industrial and scientific purposes.
A promising category of underwater 3D imagers is represented by continuous-wave amplitude-modulated laser optical radars[2,3], whose overland counterparts can achieve – in air – a line-of-sight accuracy of hundre-

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ds of micrometers at tens of meters of distance. These systems belong to the class of incoherent rangefinders. Distance d is determined indirectly through the measurement of the phase difference $\Delta\varphi$ between the modulated intensity of a laser beam – used as the carrier of a radio-frequency modulating signal – and a reference signal:

$$d = \frac{v}{4\pi f_m} \Delta\varphi \qquad (1)$$

where v is the light speed in the medium and f_m the modulation frequency. The advantage of this approach is that it requires continuous-wave, low-power laser light, making it possible to realize more robust, affordable and non-invasive devices. All pieces of information, recorded in the form of two-dimensional arrays of structured data, are then integrated and transformed into 3D images by means of dedicated software. These features make AM laser optical radars particularly well suited for applications in cultural heritage cataloguing and conservation. Actually, in this field they are widely used for the 3D digitization of both single artworks (paintings, sculptures, pottery) and entire sceneries (facades and interiors of historical buildings, archaeological sites). While nowadays AM rangefinding in air is a mature technology, the development of underwater AM optical radars is still an important scientific and technological challenge, which poses several problems in terms of reliability and attainable accuracy. This is mainly due to the non-cooperative nature of water, a much more absorbing and scattering medium than air. The intensity I_0 of a light beam propagating through water is attenuated because of absorption and scattering events due to dissolved molecules and suspended particles. In the regime of single scattering dominance, the rate of attenuation is well described by the Lambert-Beer law, which for a homogenous medium of thickness z is written as

$$I(z) = I_0 e^{-kz} \qquad (2)$$

Here $I(z)$ is the intensity of transmitted radiation and k the total attenuation coefficient. The latter, which in general depends on the radiation wavelength as well as, for inhomogeneous media, on space coordinates, accommodates for intensity losses due to both absorption and scattering. Hence it can be expressed as $k = k_a + k_s$, where k_a and k_s denote the absorption and scattering coefficients, respectively. In underwater laser imaging applications, the effect of light absorption can in principle be reduced by properly selecting the laser wavelength in the region where transmission has a maximum. For pure water, light absorption is minimal in the blue-green region of the visible spectrum (350 nm $\leq \lambda \leq$ 550 nm)[4,5]. In particular, the use of green laser light permits to reduce absorption for turbid water with a relatively abundant chlorophyll concentration, typical of coastal seawater. In the case of interest for the present work – open sea characterized by rather clean seawater – the minimum of absorption is better matched by using laser light in the violet-blue region of the visible spectrum (λ = 405 nm). The other phenomenon affecting the performances of underwater laser imagers is scattering. Light backscattered by water and falling into the angular field of view of the receiver gives rise to an undesirable signal (optical noise), which combines with the target signal carrying the information necessary to the image reconstruction. (Because of its deleterious effects on 3D imaging measures, the signal due to light backscattered by water is often referred to as optical noise in this work – though it cannot be considered noise in strict sense). The result is a reduction of the accuracy of range measurements, as well as a degradation of image contrast. It follows that optical noise has to be strongly reduced, in order to obtain 3D images of high contrast, resolution and accuracy. A partial reduction can be achieved by means of a bistatic optical layout, that is, by increasing the spatial separation between the launching and receiving stages[6]. The main drawback of this method is that it does not guarantee an effective filtering of the radiation backscattered by the initial part of the water column, which otherwise provides the most important contribution to the total noise. So, most effective rejection methods are necessary.

In this article, we present the results of research recently carried out in the ENEA Artificial Vision Laboratory (Frascati, Rome, Italy) on scattered light rejection by using modulation/demodulation and polarization techniques. The Artificial Vision Laboratory comprises researchers with a long-dating experience in the development of both coherent and incoherent optoelectronic devices, and dedicated software for artificial vision applications.

The line of research on optical noise rejection is specifically targeted at the realization of a new underwater 3D imager, the AM Underwater Laser Optical Radar. This research activity has been carried out within the BLU-Archeosys national project, funded by the Italian Ministry for University and Research. The project aims at realizing a prototype system to be mounted on a remotely-operated vehicle and used for the survey of submerged archaeological sites at depths of a few tenths of meters, i.e., in conditions of rather clear seawater.

Dependence of Optical Noise on the Modulation Frequency in Underwater AM Imagers

The experimental apparatus that has been used to validate the theoretical predictions based on a suitably developed model is shown in Figure 1. The basic device is a diode laser emitting c.w. (continuous wave) radiation at $\lambda = 405$ nm, whose output is coupled to a single-mode fiber connected to a micro-controlled scanning optics. This arrangement allows to scan with a diffraction limited focused beam a target located inside a 25 m long test tank equipped with an optical window. The portion of the laser beam reflected by the target to be visualized is detected by a receiving optics, converted into an electrical signal by a photomultiplier tube. This electrical output is the input of a lock-in amplifier device, which at the same time provides the amplitude modulation frequency f_m to the laser. The lock-in device provides a measure of the phase difference $\Delta\varphi$ between the modulated intensity of the signal beam and a reference signal.

When no target to visualize is immersed in the test tank, the bench-top system records the optical noise originating from the laser radiation backscattered by the particles dispersed in the water and falling into the field of view of the receiving optics. This signal is an optical noise which – in the presence of a target – adds to the valid signal solimiting the performance capabilities of the device. A theoretical study of our laboratory has demonstrated[7,8] that the optical noise in a device like the one described here behaves like a low-pass filter as a function of f_m. This result has been obtained by properly solving the Radiative Transfer Equations (RTEs) using a Multi-Component Approach (MCA) and under the Small Angle Approximation (SAA) and the Small Angle Diffusion Approximation (SADA). The method allows to obtain a closed expression giving the cut-off frequency f_c as a function of physical parameters of the water and of the device. It turns out that the performances of the device in term of range accuracy are expected to improve as $f_m >> f_c$.

The experiment was carried out by filling the test tank with water from the network and an attenuation coefficient $k = (0.66 \pm 0.03)\text{m}^{-1}$ was measured by using a PerkinElmer Lambda 25 UV/vis spectrometer (UV: Ultra Violet; vis: visible).

In both cases, we verified that the laser light was completely attenuated in correspondence of the tank bottom. Experimental results were compared (Figure 2) with the expected theoretical outcomes, calculated by means of the theoretical model. Theoretical and experimental data are normalized to their maximum values.

The theoretical curve in dashed line was calculated by neglecting absorption, and in the simplistic hypothesis that single scattering in the backward direction is the only attenuation mechanism. Conversely, the solid curve corresponds to the more realistic conditions where absorption and laser beam spread are taken into account. The cut-off frequency, calculated as the frequency at which the power is $1/\sqrt{2}$ of the maximum value, is $fc^{(1)} = 26.09$ MHz for the simplistic model, and $fc^{(2)} = 20.96$ MHz d for the more realistic case. On the other hand, by

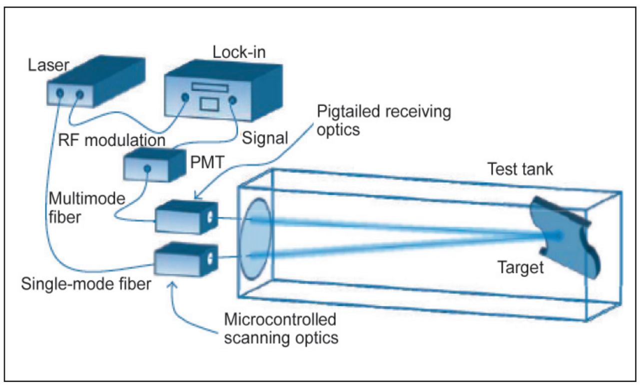
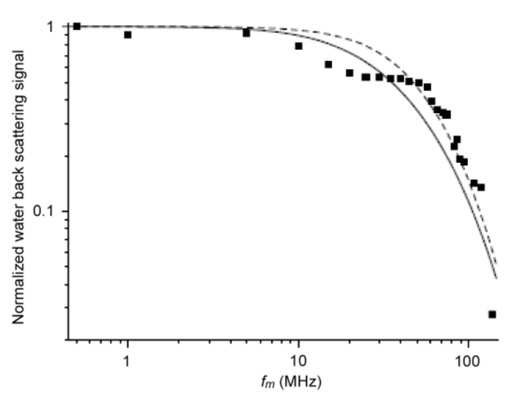


FIGURA 1 Experimental set-up of the bistatic bench-top system realized at the ENEA Artificial Vision Laboratory in Frascati
Source: ENEA



Filled squares represent the experimental measures. The other curves were obtained by means of the theoretical model

FIGURA 2 Normalized optical noise versus f_m for $k = 0.66\text{m}^{-1}$
Source: ENEA

fitting the normalized experimental data by means of the classical low-pass filter formula,

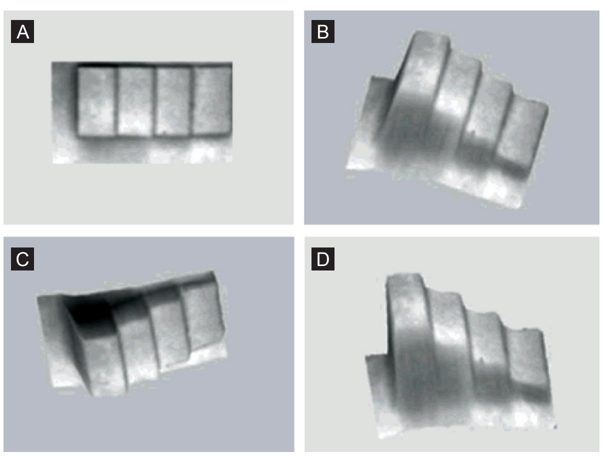
$$\frac{1}{\sqrt{1+\left(\frac{f_m}{f_c}\right)^2}} \qquad (3)$$

where f_c is a free parameter, we obtain the estimate f_c^{fit} = (20 ± 1) MHz. This value is in good accordance with $f_c^{(1)}$ and coincides, within the error, with $f_c^{(2)}$, showing that the proposed theoretical model provides a satisfactory description of the experiment, especially in the more realistic case where absorption and laser beam spread are introduced into the model.

Figure 2 confirms the expected low-pass filter trend, and clearly show that, if a phase-intensity sensitive system such as a lock-in is used for backscattered light detection, an effective optical noise rejection can be achieved by increasing the laser modulation frequency beyond the cut-off frequency. The slight yet appreciable oscillations of experimental data are possibly due to multiple backward scattering contributions not considered in the present theoretical model.

In support of this fundamental result, in Figures 3 and 4 we report the 3D images of a small dark-gray-painted, sanded, metallic ladder, both obtained in optically-thin water.

Specifically, in Figure 3 the target was immersed in clean tap water (k = 0.06m^{-1}) at a 1.5m distance from the receiver. Incident light was modulated at frequency f_m = 36.7 MHz, higher than water cut-off frequency[3]. The other image was obtained in conditions of relatively turbid water (k = 0.3m^{-1}) with a 3.7 m target-receiver distance. In this case the modulation frequency f_m = 50 MHz was just beyond the expected cut-off value. Both pictures are of good quality, and rather faithfully reproduce the original target. A slight degradation of the pha-



Note that the ladder is shown with various orientations

FIGURA 3 Underwater 3D images of dark-gray-painted, sanded, metallic ladder immersed in clean water (tap water) at a 1.5m distance from the receiver, obtained by working at f_m = 36.7 MHz
Source: ENEA

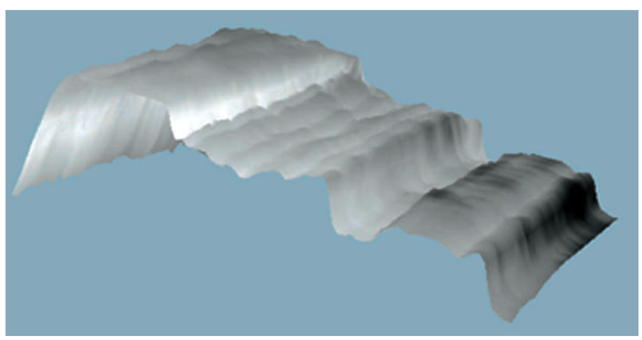
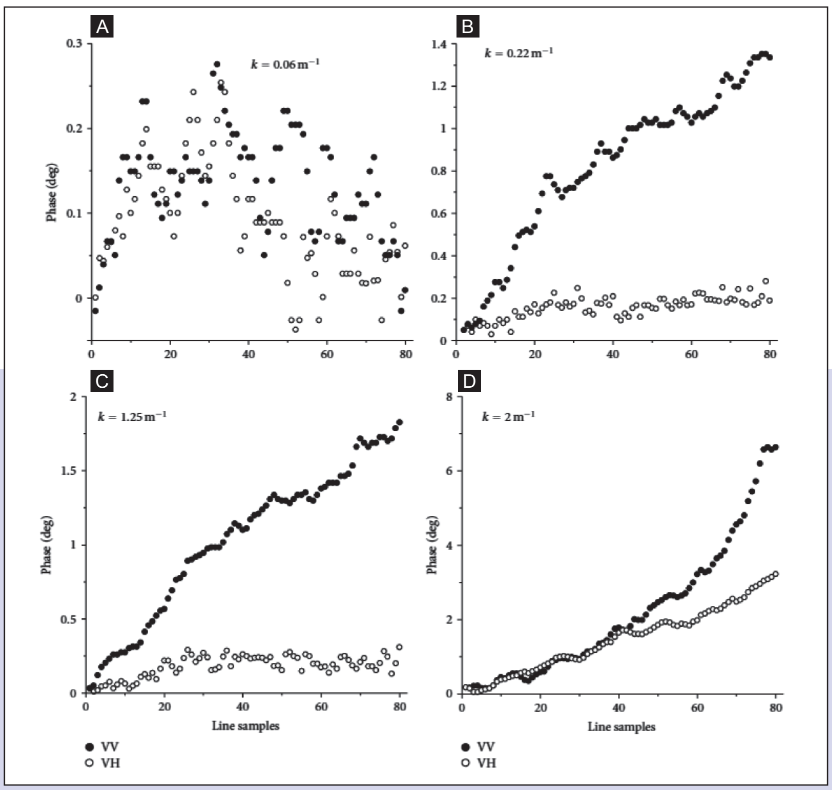


FIGURA 4 Underwater image of dark-gray-painted, sanded, metallic ladder immersed in relatively turbid water (k = 0.3m^{-1}) at a 3.7m distance from the receiver, obtained by working at f_m = 50 MHz
Source: ENEA

se (i.e., distance) measurement accuracy is observable in Figure 4, evidenced by a rougher and less sharp reproduction of the ladder.
This can be attributed to the much higher optical thickness of the medium in this case, with a consequent increase in the cut-off frequency, that would have required to operate at a much higher modulation frequency.

Optical Noise Rejection through Polarimetry

In this section we report a series of underwater 3D images and linear phase profiles, obtained by using the system of Figure 1. Specifically, it is equipped with suitable polarizer configurations on the launching and receiving stages and a 1.56m Plexiglas test tank, with source-receiver separation r_{rec} =7 cm. The experiments were aimed at demonstrating the validity of the polarimetric technique as an effective means to reduce the effect of optical noise on both intensity and phase measures. The method relies on the fact that, at least in certain conditions, linearly-polarized incident light is partially depolarized by the target, while backscattering off the medium conserves the polarization state. Beside underwater imaging, other application fields of this method are remote sensing[9] and biomedical studies[10], where its effectiveness is demonstrated.
A first series of experiments were carried out by perpendicularly sweeping a polarized AM laser beam on a mostly diffusive target consisting of a dark-gray-painted, flat, metallic plate. The target was immersed on the bottom of the tank, in water of varying turbidity degrees obtained by adding suitable quantities of skim milk (1.5wt.% fat content) to tap water. The polarization scheme investigated was incident light in vertical linear polarization state, and receiving stage in either co-polarized (VV) or cross-polarized (VH) configuration.



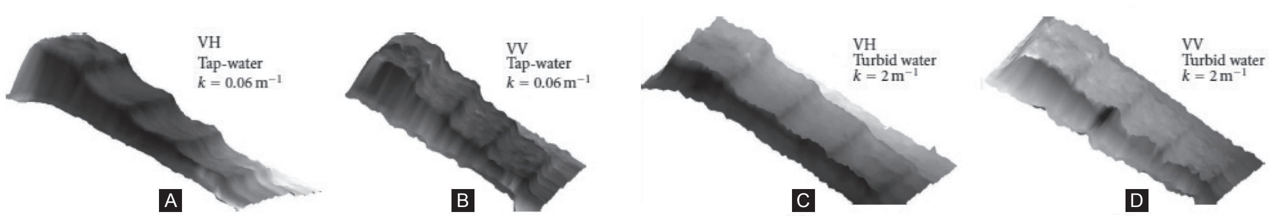
The AM laser beam (f_m = 39 MHz) was linearly polarized perpendicularly to the reference plane (vertical linear polarization)

FIGURA 5
Linear-phase profiles of a flat metallic target (z_T = 1.56 m) corresponding to VV (filled circles) and VH(open circles) schemes, for water of various turbidity levels
Source: ENEA

In all cases phase profile lines were acquired, each comprising 80 phase measurements (pixels) with a sampling time per pixel of 100 ms. Each scan line covered a horizontal 10cm segment on the target. Owing to the system's bistatic layout, pixels #1 and #80 corresponded, respectively, to the conditions of minimum and maximum overlapping between the receiver's field of view and the beam path in water, that is, to minimum and maximum contribution of the optical noise. For each line, the phase was set to 0° in correspondence of pixel #1. Deviations from this value during line scanning (phase drift) were taken as an indication of the optical noise rejection efficiency of the system-lower phase drift values corresponding to higher rejection. The results obtained by using linearly-polarized light are reported in Figure 5.

When the flat target is immersed in tap water (k = 0.06m^{-1}, clean water, Rayleigh scattering regime), there is no appreciable difference between VH and VV configurations. During the scans, the measured phase remains nearly constant within a range of 0.25°, which represents the intrinsic error of the apparatus operating at the described conditions (Figure 5(a)). This occurs because the light backscattered by the tap-water column (optical thickness τ = 0.0936) is negligible if compared with the radiation reflected by the target. In fact, in these conditions, the albedo for single scattering events, that represents the fraction of energy lost from incident beam due only to scattering, is close to zero. The situation drastically changes for k = 0.22m^{-1} (τ =0.34), when the condition of quasi-Mie (or intermediate) scattering regime is approached and the light scattered by the medium strongly increases. Along the whole scan line in VH configuration, the phase remains constant within the accuracy error. Conversely, in the VV scheme it grows almost linearly, reaching the value of 1.3° in correspondence of pixel #80, where the detector sees the entire water column (Figure 5(b)). Analogous results are found for k = 1.25m^{-1} (Figure 5(c)), where single scattering events still dominate and the medium optical thickness is τ = 1.95 < 10. In these conditions, the radiation backscattered off water preserves the linear polarization state of the incident light. On the contrary, the target depolarizes, that is, randomly changes the polarization state. As a consequence, the VH detection scheme is more effective in rejecting the optical noise, since in this configuration backscattered light of vertical linear polarization is filtered out, enabling to obtain phase measurements of higher accuracy. For k = 2m^{-1}, the medium optical thickness raises up to τ = 3.12, approaching the transition scattering regime, with a higher probability of multiple scattering events. In this case, also the light backscattered by the medium is partially depolarized. Consequently, the noise rejection mechanism is less efficient, and the phase measured in the VH configuration presents a nearly-linear drift from 0° to 3°. Also in this case, though, the cross-polarized scheme gives better results than the co-polarized one, where the phase drift reaches the value of about 7° on the receiver edge (Figure 5(d)).

A second group of scans (Figure 6) were performed in similar conditions, but on a different target, namely a dark-gray painted, sanded, metallic ladder. The ladder had 1 cm-high steps, apart from the first step whose



The ladder was alternatively immersed in clean (tap water) and turbid water at 1.5m from the receiver

FIGURA 6 3D images of the ladder, obtained by using cross-polarized (VH) and co-polarized (VV) working schemes
Source: ENEA

height was 4 cm. In this case, we only used V-linearly polarized incident light, in combination with both co-polarized (VV) and cross-polarized (VH) detection configurations. Two series of measurements were carried out by using, respectively: (1) tap water (k = 0.06m^{-1}) and (2) a mixture composed of tap water and skim milk (k = 2m^{-1}). In both cases the medium could be considered optically thin. In each scan, 40 × 80 arrays of data were acquired by sweeping the laser probe (f_m = 39MHz) perpendicularly onto the target, with a sampling time per data element of 125 ms.
Specifically, 3D images recorded in the cross-polarized (VH) linear working scheme (Figure 6(a) and 6(c)) better evidence phase measurement accuracy, contrast, spatial resolution (of the order of millimeter at 1.5m), as well as less phase noise compared to 3D models recorded by using the co-polarized (VV) linear working configuration (Figure 6(b) and 6(d)). In the latter case, the steps look rougher and the ladder structure is smoothed due to the higher contribution of optical noise, especially for k = 2m^{-1}. In summary, also these results confirm that, at least for an optically thin medium, more effective optical noise rejection is achieved both in clean and turbid waters by using a cross-polarized (VH) rather than a co-polarized (VV) detection scheme.

Conclusions

Beside confirming the soundness of the theoretical framework developed by the theoretical group of the laboratory, the experimental results presented in the last sections clearly illustrate the importance of optical noise rejection for underwater 3D imaging applications. Specifically, we showed that, in optically-thin turbid water and in conditions of intermediate or quasi-Mie scattering regime, the contrast and phase accuracy of 3D images can be considerably improved by reducing the contribution of the optical noise.This this does not seem to be critical for clean water (Rayleigh scattering regime), at least for target distances within 3.7m. We demonstrated both theoretically and experimentally that, for underwater AM imagers that are only sensible to the modulated part of the received power, the signal due to the backscattering of light by the medium has a low-pass filter dependence on the modulation frequency. The cut-off frequency is generally a complicated function of both the optical properties of the medium and the characteristics of the detection system. Hence it can be difficult, in practical situations, to identify an operational value for f_m that falls with certainty beyond the cut-off frequency. Nonetheless, the results obtained give clear indications in favor of using the highest possible modulation frequency in any real situation. The results here reported have been extensively used during the several stages that are leading to the realization of a prototype suitable to operate in subsea conditions. The firsts trials of this prototype in open sea are scheduled for summer 2011 and expected to further shed light on the efficiency of the methods proposed.

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