Development of a hologram optical element for lidar

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Abstract. In this paper, we propose to use the concept of a scanning telescope using a holographic optical element in lidar to measure the height of the lower boundary of the clouds, the advantages of which are to reduce the size and weight of lidar, reducing the cost of the device and increase productivity, simplifying the work on alignment and calibration. A method of calculating the parameters of a hologram optical element is proposed.

1. Introduction
Cloudiness refers to the priority objects of study in atmospheric physics and climate-ecological monitoring. The cloud monitoring system includes a network of both terrestrial and space observations, providing a continuous series of observations on the main objects of climate and environmental monitoring [1-3]. In the complex set of meteorological elements and phenomena involved in the formation of weather and climate, clouds play a decisive role. Therefore, it is important to monitor the parameters of clouds, such as their number, shape, direction of movement and repeatability on all tiers, water content, horizontal and vertical length, etc. The lower and upper cloud boundaries are among the most important parameters describing the state of cloudiness at certain points in time. Continuous series of observations of the height of the lower and upper cloud boundaries, along with other parameters characterizing the state of cloudiness, are used in the synoptic-climatic cloud models. In addition, the clouds have a significant impact on man's technogenic activities associated with the use of airspace of the earth. For example, in the meteorological support of aviation, the height of the lower cloud boundary, along with the range of visibility, is one of the most important parameters in the operational meteorological minimum of the aerodromes, which determines the mode of their operation [4-6]. Instruments and apparatus for monitoring the current state of the atmosphere from the earth's surface have found wide application both in operational practice and in scientific research related to the study of the structure of the atmosphere and the dynamic processes taking place in it. At the same time, the improvement and creation of new remote methods and instrumentation complexes for remote control of the atmosphere and clouds remains one of the most promising areas for the development of meteorological instrumentation.

2. The construction of the lidar
In this article, it is proposed to improve the lidar design for measuring the height of the cloud bottom using a holographic optical element (GOE) as a scanning objective.

Typically, lidars require a large collecting aperture in order to maximize the backscattering signal of the laser and the narrow field of view necessary to limit the amount of background radiation reaching the detector. The advantage of GOEs is that they can use opaque substrates to support a...
holographic film or pattern, which opens the possibility of using ultra-light materials such as graphite epoxy resins and similar composites, so we can reduce the overall dimensions and weight of the lidar, which will entail not only reduce the cost of the device, but also increase its performance, simplify the work on alignment and calibration.

In this regard, we present to your attention the concept of a scanning telescope using a holographic optical element (GOE). [7-9]

In the design under consideration, the conventional optical telescopic optics and the scanning mirror are replaced by a single GOE. In the optical scanning device (Fig. 1), an optical energy source (laser) is used and a rotating GOE having a rotation axis perpendicular to the plane of its substrate and a fixed focus that is located on its axis of rotation. In doing so, the GOE diffracts the source of optical energy at an angle to its axis of rotation, providing a conical scanning area.

![Figure 1. The optical scanning device.](image)

3. Calculation of holographic optical element
The hologram optical element should not distort the path of the rays in and out of the optics, but simply redirect them, obeying a certain law that is the same for all directions of the ray path; should ensure the equivalence of the released radiation to the incoming, as well as ensure the obtaining of an exit pupil uniform in the field and within the region of the exit pupil. [10, 11]

![Figure 2. Input and output of radiation into the hologram plate.](image)

The task of this calculation is to determine the main parameters of the hologram plate (glass grade, thickness, parameters of the GOE), and also to determine the requirements for the parameters of the circuit (exit pupil size, angle of field) working in conjunction with this element. [12,13,14] Initially, we define the angle of total internal reflection of the hologram plate:

\[
\alpha_{TIR} = \arcsin \left( \frac{n_2}{n_1} \right)
\]
where \( n_2 \) and \( n_1 \) - the refractive indices of the glass and the medium from which the rays enter the glass. Since the GOE is a diffraction grating, to determine their period, we write down the lattice formula:

\[
d_{\text{grat}} (n_{gl} \sin \alpha + n_1 \sin \theta) = m\lambda,
\]

(2)

where \( n_{gl} \) - refractive index of glass; \( n_1 = 1 \) - air refractive index; \( \theta \) - angle of diffraction on a lattice; \( \alpha \) - angle of propagation of radiation on a plate; \( \lambda \) - radiation wavelength.

Taking into account that the radiation propagates in the plate at an angle of total internal reflection, we obtain:

\[
n_{gl} \sin \alpha \geq n_1,
\]

(3)

Substituting expression (3) into (2), we derive a formula for determining the period of the gratings that make up the plate of the hologram element:

\[
d_{\text{grat}} = \frac{\lambda}{1 + \sin \theta_{\text{max}}}
\]

(4)

From the formula (2) we define the maximum angle of entry of the radiation diffracted on the input grating into the plate, which in the future will be necessary for us to estimate the size of the exit pupil of the system.

\[
\sin \alpha_{\text{max}} = \frac{d_{\text{grat}} \sin \theta_{\text{max}}}{n_{gl}}
\]

(5)

Then we determine the distance between the neighboring reflections of the ray:

\[
L_0 = 2d_{\text{grat}} \tan \alpha_{\text{max}}
\]

(6)

where \( d_{\text{grat}} \) - plate thickness, \( \alpha_{\text{max}} \) - the maximum angle of the beam entrance into the hologram plate.

We give several calculations and the derivation of the corresponding dependences.

For example, we use the glass grades TF4, TF7, whose refractive index is \( n_{gl} = 1.73 \), the angle of the field \( \theta = 5^\circ \), then

\[
\begin{align*}
\alpha_{\text{for}} &= \arcsin \left( \frac{1}{n_{gl}} \right) = \arcsin \left( \frac{1}{1.74} \right) = 35.3^\circ \\
\alpha_{\text{max}} &= \arcsin \left( \frac{(1 + 2 \cdot \sin \theta_{\text{max}})}{n_{gl}} \right) = 42.7^\circ
\end{align*}
\]

(7)

(8)

Period of input and output gratings:

\[
d_{\text{grat}} = \frac{\lambda}{1 + \sin \theta_{\text{max}}} = \frac{0.532}{1 + \sin 5^\circ} = 0.489 \text{ mkm}
\]

(9)

The period of the intermediate grating for turning the radiation on \( 45^\circ \) to maintain the step of the pupil’s examination differs from the period of the input and output gratings and is calculated from formula (5):

\[
d_{\text{in}} = d_{\text{grat}} \sqrt{2} = 0.346 \text{ mkm}
\]

(10)

To provide two given periods of gratings for a symmetric acquisition circuit, the angles of the circuit are respectively equal to:

\[
\begin{align*}
\gamma &= 2 \cdot \arcsin \left( \frac{\lambda}{2d_{\text{grat}}} \right) = 2 \cdot \arcsin \left( \frac{0.4416}{2 \cdot 0.489} \right) = 53.6^\circ \\
\gamma' &= 2 \cdot \arcsin \left( \frac{\lambda}{2d_{\text{in}}} \right) = 2 \cdot \arcsin \left( \frac{0.4416}{2 \cdot 0.345} \right) = 79.3^\circ
\end{align*}
\]

(11)

(12)

4. Conclusion

The article suggests using the concept of a scanning telescope with the use of a holographic optical element in the lidar to measure the height of the lower cloud boundary, the advantages of which will lead to a reduction in overall dimensions and weight of the lidar, a reduction in the cost of the instrument and increase its productivity, simplify the work on alignment and calibration. The
dependences between the main parameters of the light guide plate are calculated (Table 1). The dependence of the refractive index of the glass of the hologram element on the angle of the TWO is analyzed, the larger the refractive index of the glass of the substrate, the smaller is the minimum angle of the TIR and, correspondingly, the maximum angle of the radiation input into the hologram plate (Figure 3). It follows from Table 1 that this scheme for constructing a holographic optical element can provide field angles of 30 degrees and higher, but it is necessary to use glasses with a high refractive index.

Table 1. Dependence between the main parameters of the light guide plate.

| № | Field, deg | $n_{gl}$ | $d_{ave}$, mkm |
|---|------------|----------|----------------|
| 1 | $\pm 5^\circ$ | 1.62 | 0.49 |
| 2 | $\pm 5^\circ$ | 1.73 | 0.49 |
| 3 | $\pm 10^\circ$ | 1.62 | 0.45 |
| 4 | $\pm 10^\circ$ | 1.53 | 0.45 |
| 5 | $\pm 7^\circ$ | 1.62 | 0.47 |
| 6 | $\pm 7^\circ$ | 1.53 | 0.47 |
| 7 | $\pm 5^\circ$ | 1.53 | 0.49 |
| 8 | $\pm 15^\circ$ | 1.71 | 0.42 |
| 9 | $\pm 15^\circ$ | 1.74 | 0.42 |
| 10 | $\pm 18^\circ$ | 1.74 | 0.406 |

Figure 3. Dependence of the angle of air defense on the angle of refraction of glass.

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