CONCLUSION

The range of problems that are successfully solved with the use of laser systems has grown considerably in recent years. The expanding application of current optoelectronic and adaptive optics systems is state-of-the-art optics. Historically, adaptive optics was first used in astronomy and more recently in ground-based systems for imaging artificial satellites and other space objects, but now other efficient applications are being reported increasingly often. In our opinion, in the near future adaptive optics will be widely used in a number of areas. Current adaptive optics can produce breakthroughs in industrial technologies and medicine. The performance of optoelectronic devices in manufacturing and medical applications (such as welding and cutting, drilling metal and extrahard materials, laser scalpels, or optical systems in ophthalmology) that employ coherent processing of signals can be considerably improved through implementation of adaptive optics elements and systems.

However, the development of optoelectronic systems is a rather long process that usually proceeds in the absence of complete information on the peculiarities of the medium of propagation. Also, modern optoelectronic systems are rather expensive because at the initial stage of their design they require calculating and estimating the efficiency of applying various algorithms and programs that are based on current adaptive optics technologies. The main parameters of such systems can hardly be changed during their operation. This forces designers to keep in mind possible changes in the system's main parameters at different stages of design and production.

The feasibility of sufficiently flexible adjustment of optical system parameters is now one of the main requirements in designing optoelectronic devices, and this feasibility is provided by adaptive optics systems. This is because a change in the main parameters of an optical system can be made simply by replacing the operational algorithm of an adaptive system.

The creation of optical systems necessarily includes designing the systems and determining the possibilities of their application under actual atmospheric conditions. In this book we have described these stages, taking into account present-day achievements.

Adaptive optics systems differ from other systems in the elements included in the optical scheme: a wavefront sensor, an active optical element (active mirror), and a reference source supplying information on fluctuations and the radiation propagation channel. Each element of the optical scheme calls for precalculations; therefore, calculations of not only the parameters of adaptive optics, but the system as a whole are often needed. Corresponding calculations are performed for the wavefront sensor, active mirror, and certainly the reference source formed in the propagation channel of the optical radiation to be corrected.

One of the ways to create a reference source is to use a signal backscattered from atmospheric inhomogeneities. Various schemes for formation of a reference source (a laser guide star) for imaging purposes have been described. In this book, we discussed the limited capabilities of image correction using a signal based on measurement of the LGS position. The direct use of an LGS signal for full-aperture tip-tilt correction is impossible because the valid signal should be first separated from the data of optical observations of LGS image jitter. This aspect of the problem was described in detail in this book with allowance made for modern advances in this field. Earlier, attempts were undertaken to systematize numerous approaches solving the problem of LGS tilt retrieval for an adaptive optics scheme operating against an LGS signal. We have considered here a "general" scheme for forming a laser guide star.

Since numerical simulation of optical wave propagation through the atmosphere is now one of the main methods for studying and designing modern optoelectronic systems, we have paid considerable attention to describing the computational algorithms that can be used in software packages for modeling the adaptive control of laser beams and imaging systems in the atmosphere. The propagation of optical radiation through a randomly inhomogeneous medium is simulated using a numerical solution of the wave equation written in the parabolic approximation for the scalar complex amplitude of the optical field and the field of the refractive index of the medium. When dynamic and nonlinear problems are modeled, the wave equation is solved together with some material equation describing how the state of the medium changes in time. In our calculations we use the modified splitting method and the fast Fourier transform algorithm.

The algorithms and programs developed by us allow the operation of an optoelectronic system to be modeled as a whole. It becomes possible to describe such phenomena as nonstationary thermal blooming, in which the refractive index of the medium varies because the medium is heated by the laser radiation propagating through it. The algorithms proposed here make it possible to model the evolution of the temperature field by taking into account two mechanisms: forced convection (in the arbitrary direction of the wind velocity) and molecular heat conductivity; this is very important if there are dead zones on the path of the laser radiation.

To take into account the effect of turbulent fluctuations of the atmospheric refractive index on the propagation of laser radiation (the laser beam), we model two-dimensional randomly inhomogeneous phase distortions of the wavefront with a spectral density corresponding to the Kolmogorov model of the turbulence spectrum that accounts for the finiteness of the inner and outer scales of turbulence. According to the Kolmogorov–Obukhov hypothesis, the structure function in fluctuations of temperature and the atmospheric refractive index obeys the power law. The finite values of the inner and outer scales of turbulence were introduced in the calculations. The ratio of these scales is taken, as a rule, to be equal to 1000. The structure function depends on the intensity of turbulent distortions. In the atmospheric surface layer ($h < 20$ m) this intensity decreases with height, and the character of this height dependence changes with meteorological conditions. This significantly complicates the development of a single universal model. We use several models, including a rather simple empirical model obtained from experimental data (up to 20 km) under the conditions of best, medium, and worst visibility.

The conditions of propagation of laser radiation through the atmosphere include such characteristics as the position of the laser source and the position and motion of the receiver. The atmosphere is modeled as a stratified medium. The variable parameters of the problem are the altitude of the laser source, the initial radius of the beam, the radiation intensity at the optical axis, the intensity distribution profile of the optical beam, the altitude of the receiver, the zenith angle of the propagation path, and the azimuth and scanning rate of the laser source.

To take into account the vertical variability of atmospheric parameters entering into the equations to be solved, we propose to use the standard models of the atmosphere that allow for physical and geographical conditions, as well as spatiotemporal variations of meteorological parameters based on statistical measurements over many years.

The atmospheric air is assumed to be an ideal gas of a constant composition that is described by the state equation, including pressure, density, and temperature. The atmosphere is divided into the following layers: troposphere, stratosphere, mesosphere, and thermosphere. The altitude profile of the temperature for each layer is approximated by a linear function of the geopotential altitude. The vertical profile of the air density is calculated from the given profiles of temperature and pressure based on the state equation of the ideal gas.

Because of considerable spatiotemporal variability of the wind in the atmosphere, when solving applied problems we think it is worth using the data from online sensing of the path along which the optoelectronic system will operate. However, to evaluate the efficiency of adaptive optics systems designed to operate through the atmosphere, it is quite sufficient to restrict consideration to the models of the wind structure that were obtained from long-term measurements at sensing stations.

Since molecular absorption of laser radiation in the atmosphere has pronounced frequency dependence, a line-by-line calculation is now the most universal and accurate method for determining absorption characteristics.

Actual adaptive optics systems employ several types of sensors, including the Hartmann sensor, to record phase distortions. We propose a specialized sensor based on the Hartmann algorithm. We use up-to-date approaches to develop a stable phase reconstruction algorithm, in particular for strong intensity scintillations, as well as algorithms for phase “joining” under dislocation conditions.

We have analyzed a wide range of control elements with different degrees of freedom, geometries of mutual arrangement, and frequencies and spatial fluctuations of the response of every control element. In this analysis we included mirrors for tip-tilt correction of the optical beam as a whole. In addition, we have studied various active and adaptive mirrors: zonal and modal correctors and segmented mirrors of different geometries, as well as a static model of a flexible mirror and a numerical model of a dynamic mirror.

The authors hope that this book will be interesting for its readers. It will be useful for specialists dealing with the development of devices and elements of adaptive optics systems.

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