Šíření mikrovln v prostředí působení harmonických a rázových akustických vln

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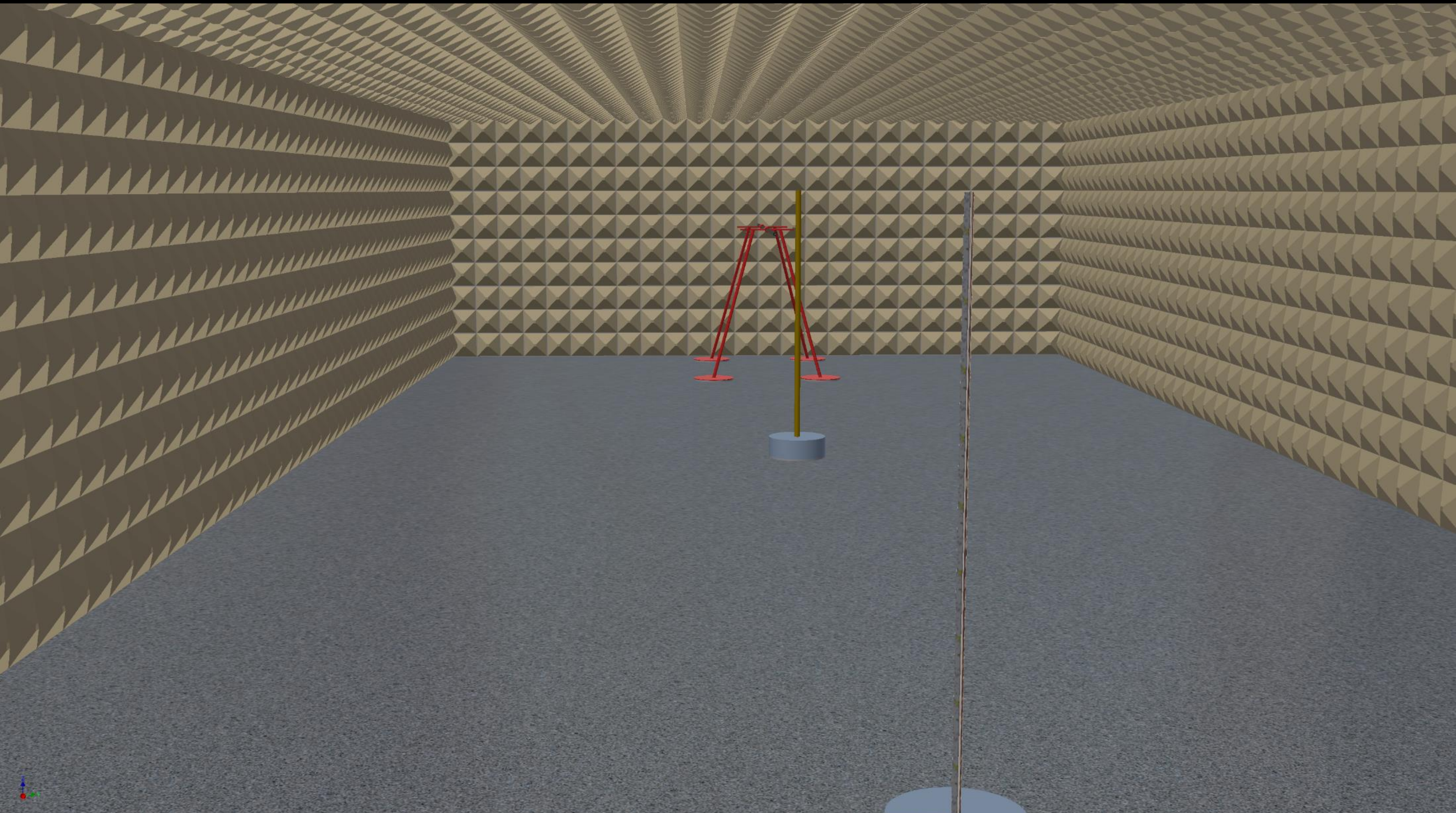
Setkání uživatelů COMSOL Multiphysics 2019

Bořetice (23. a 24.) května 2019

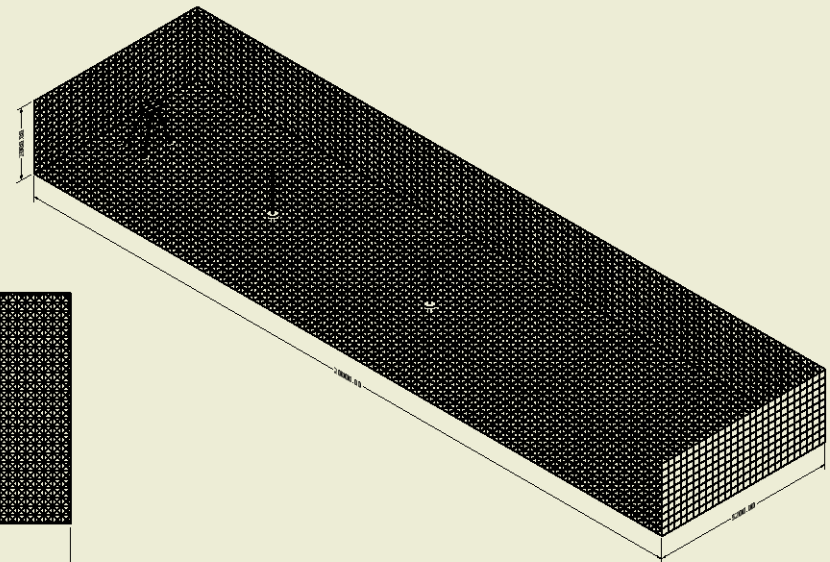
Model experimentu

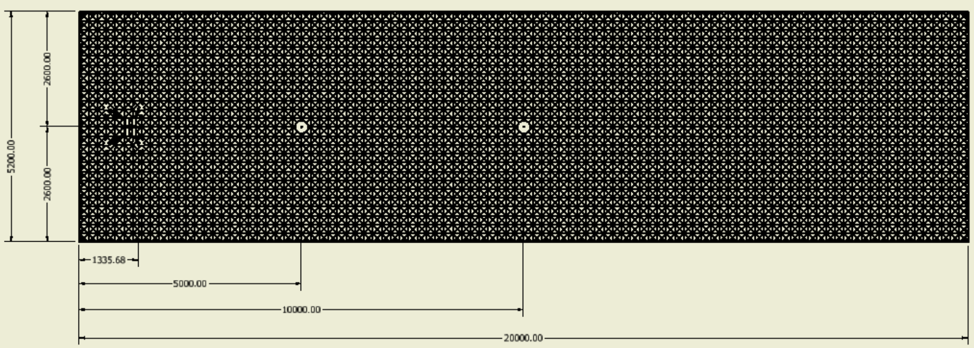
Cíle:

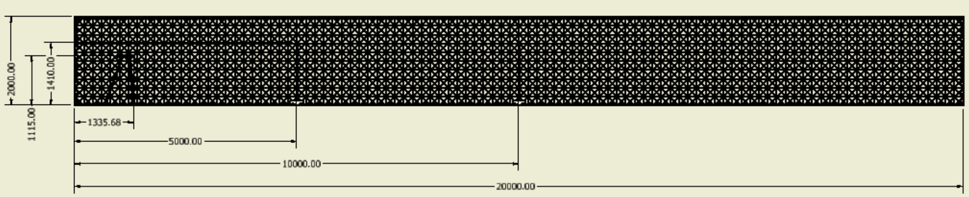
1. Plán experimentu
2. Interpretace experimentálních dat



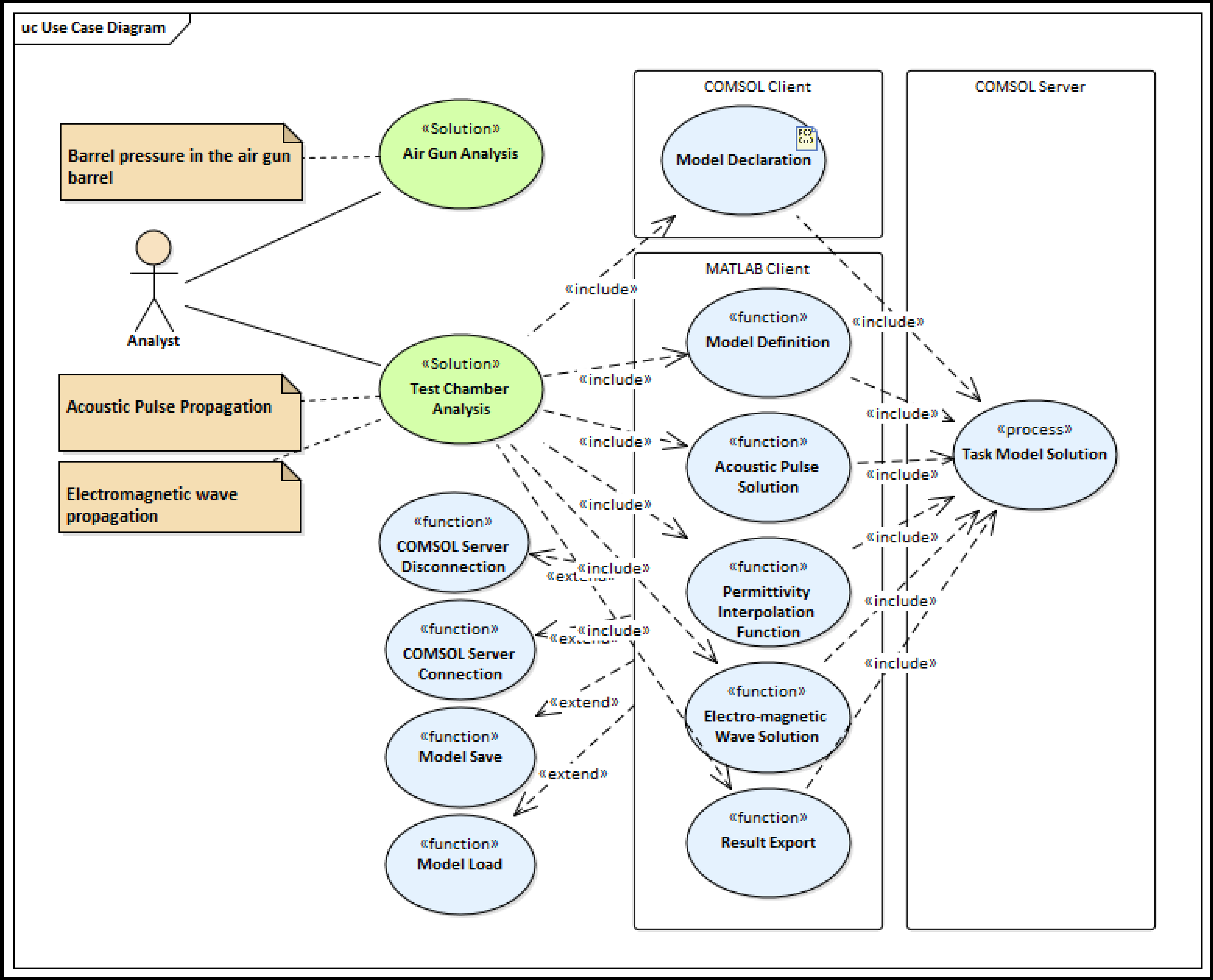
Uspořádání experimentu



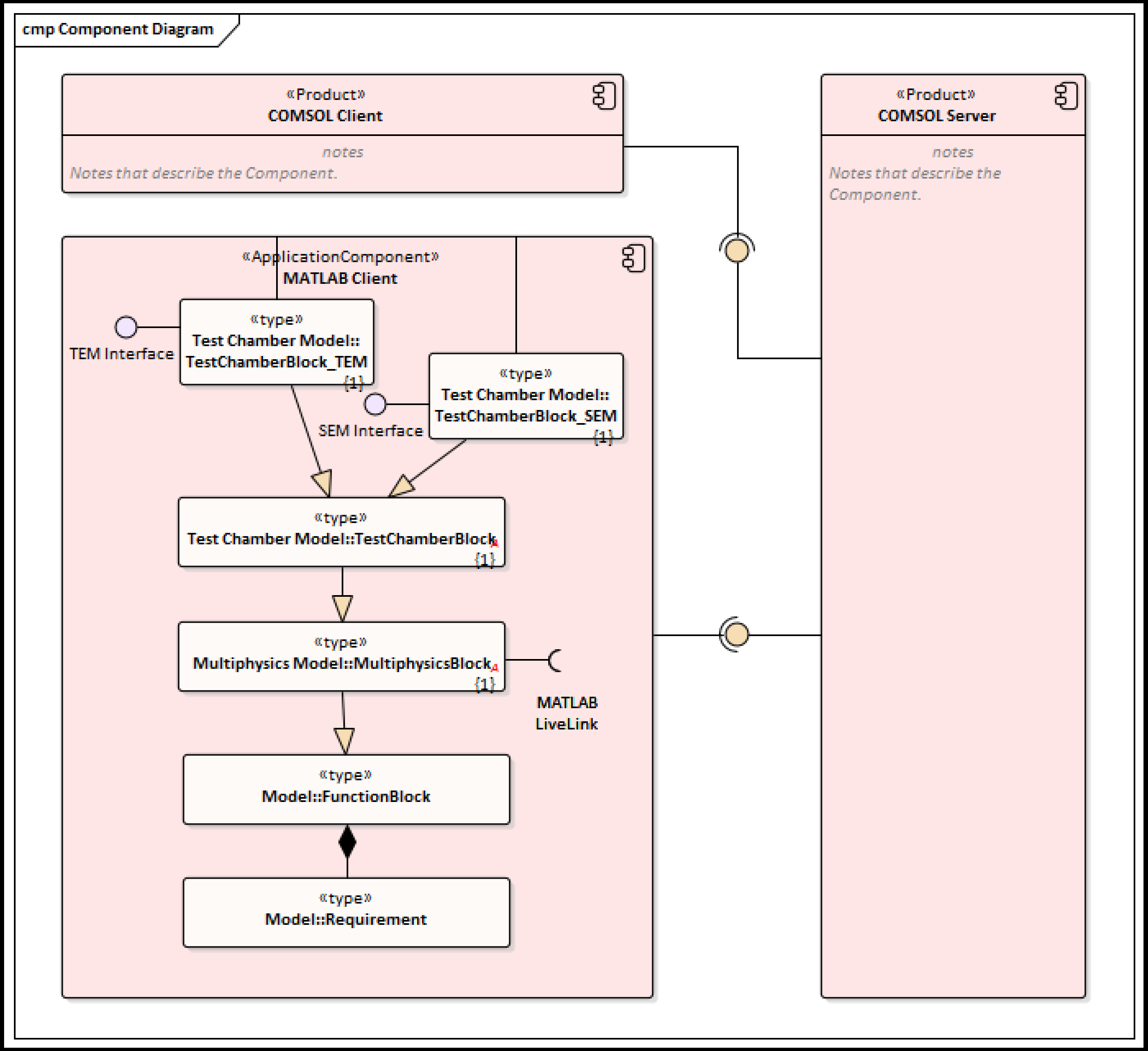




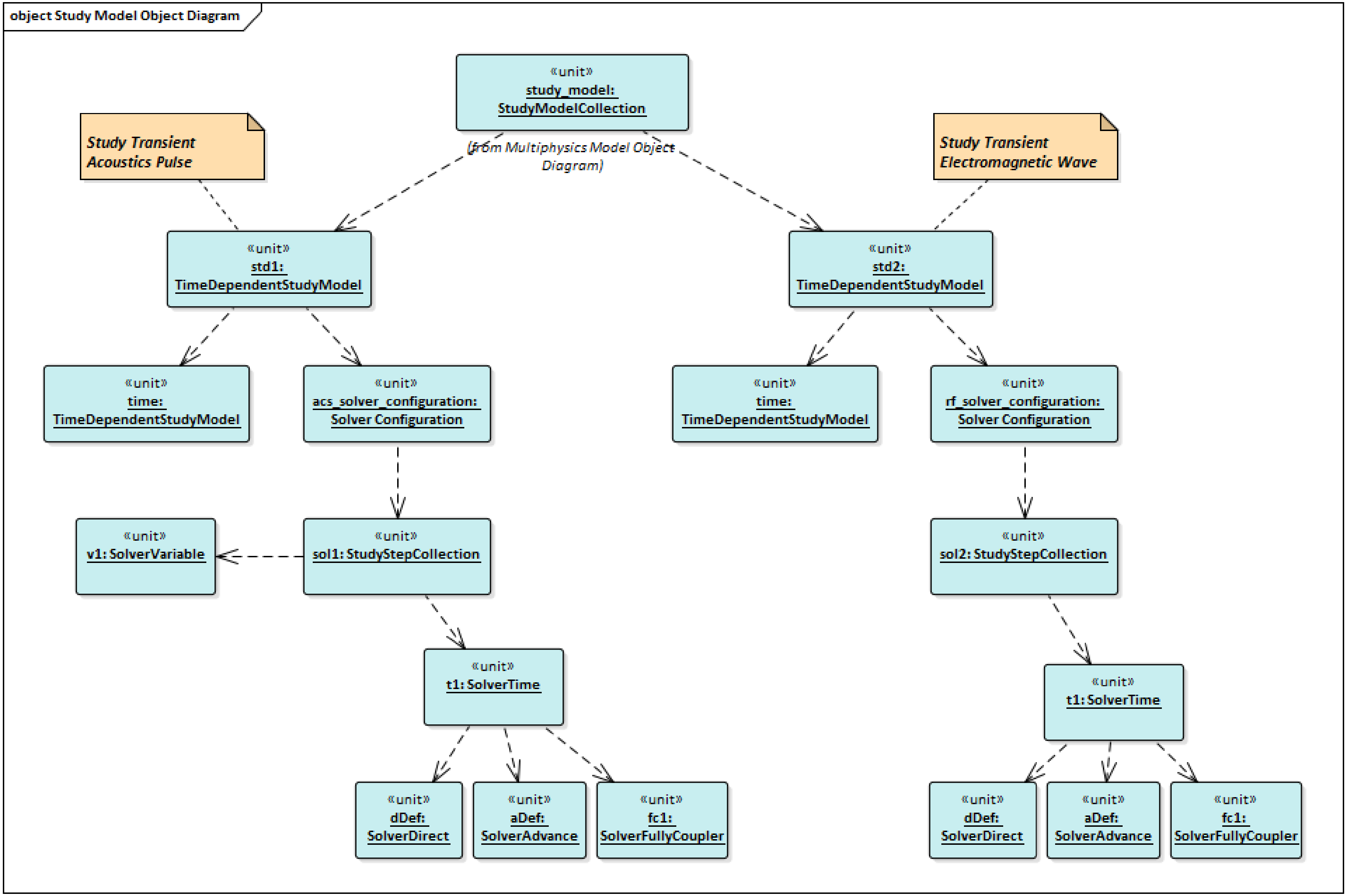
Postup řešení



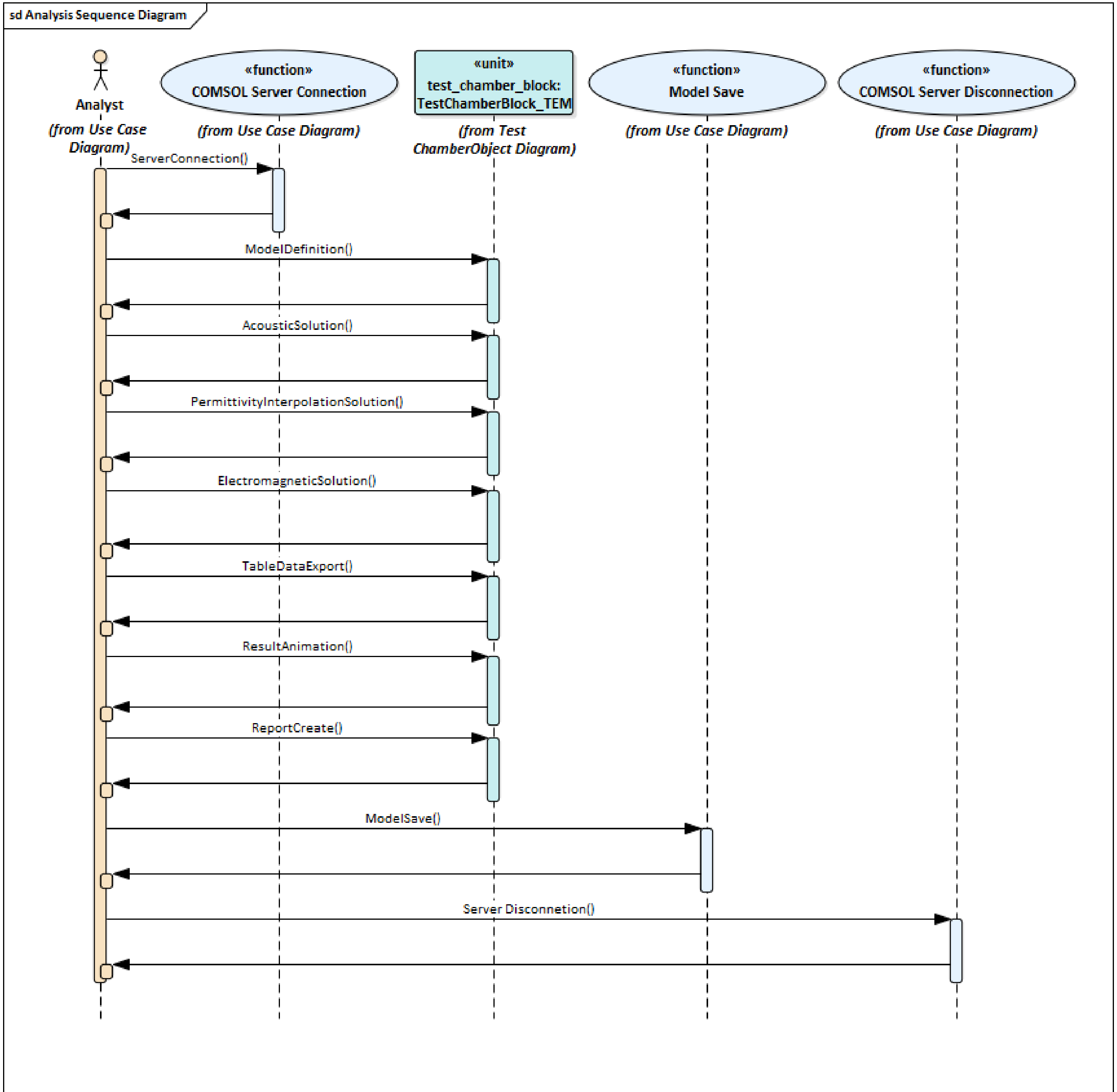
Komponenty řešení



Statická struktura řešení



Sekvence řešení

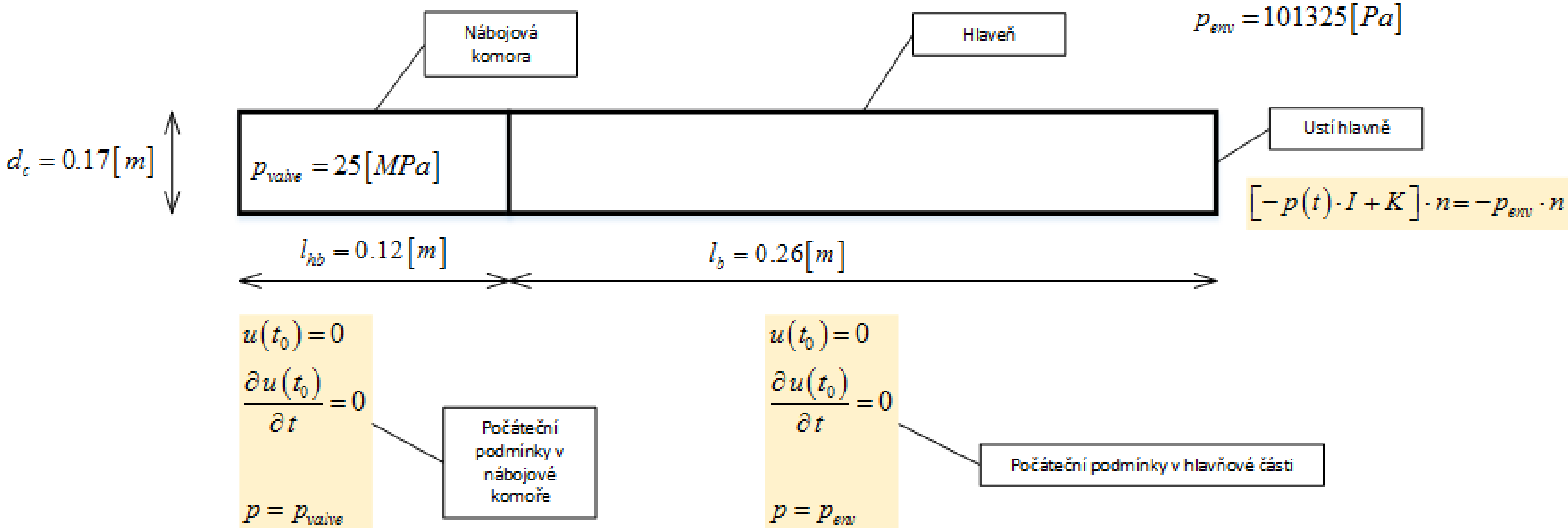


Dynamika pohybu vzduchu ve vzduchovém dělu

$$\frac{\partial \rho(t)}{\partial t} + \nabla \cdot \left(\rho(t) \cdot u(t)\right) = 0$$

$$\rho \cdot \frac{\partial u(t)}{\partial t} + \rho \cdot \left(u(t) \cdot \nabla\right) \cdot u(t) = \nabla \cdot \left(-p(t) \cdot I + K\right) + F$$

$$K = \mu \cdot \left(\nabla \cdot u(t) + \left(\nabla \cdot u(t)^T\right)\right) - \frac{2}{3}\mu \cdot \left(\nabla \cdot u(t)\right) \cdot I$$



$$p_{env} = 101325[Pa]$$

$$d_c = 0.17[m]$$

$$p_{valve} = 25[MPa]$$

$$\left[-p(t) \cdot I + K\right] \cdot n = -p_{env} \cdot n$$

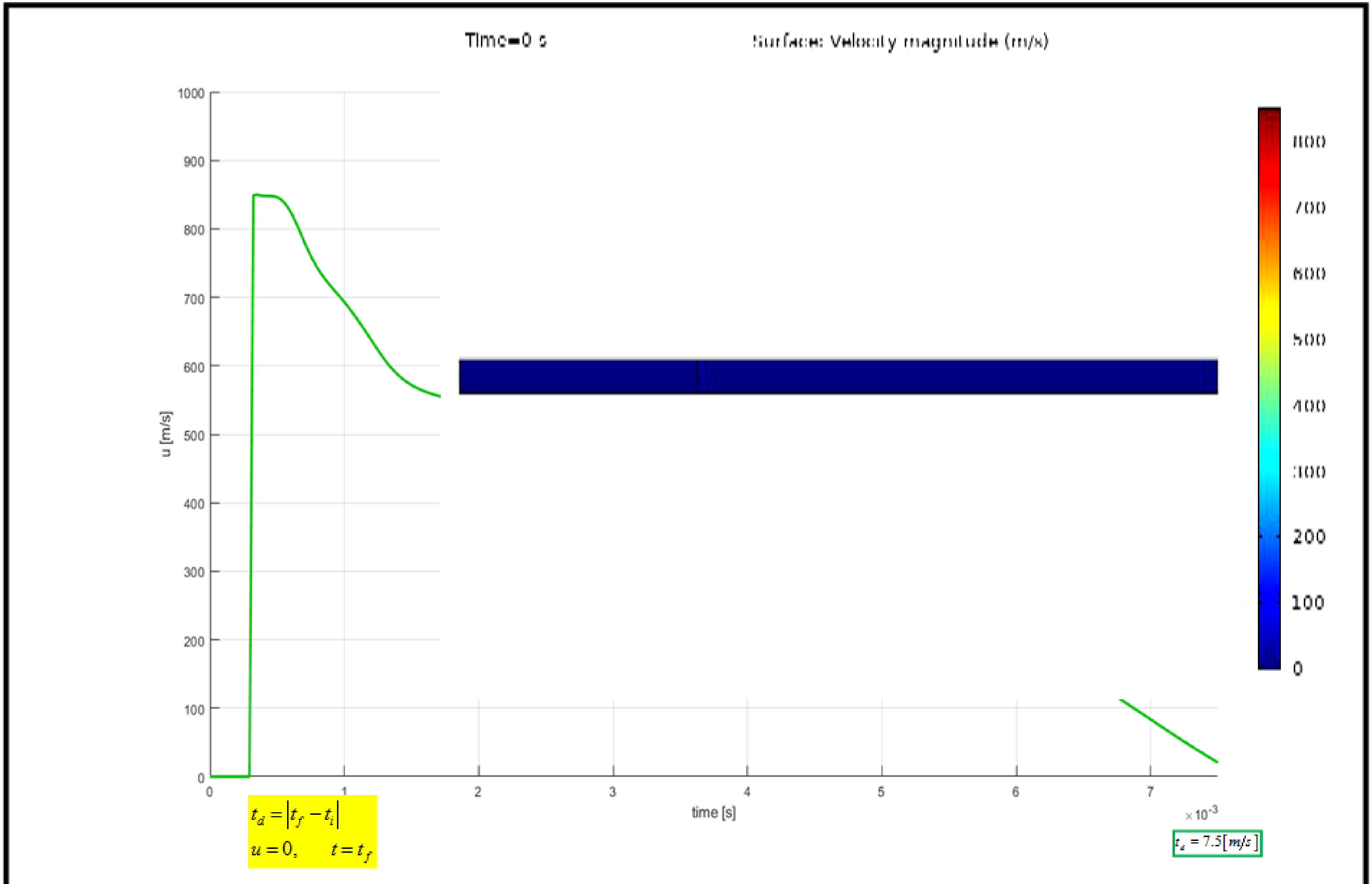
$$l_{hb} = 0.12[m]$$

$$l_b = 0.26[m]$$

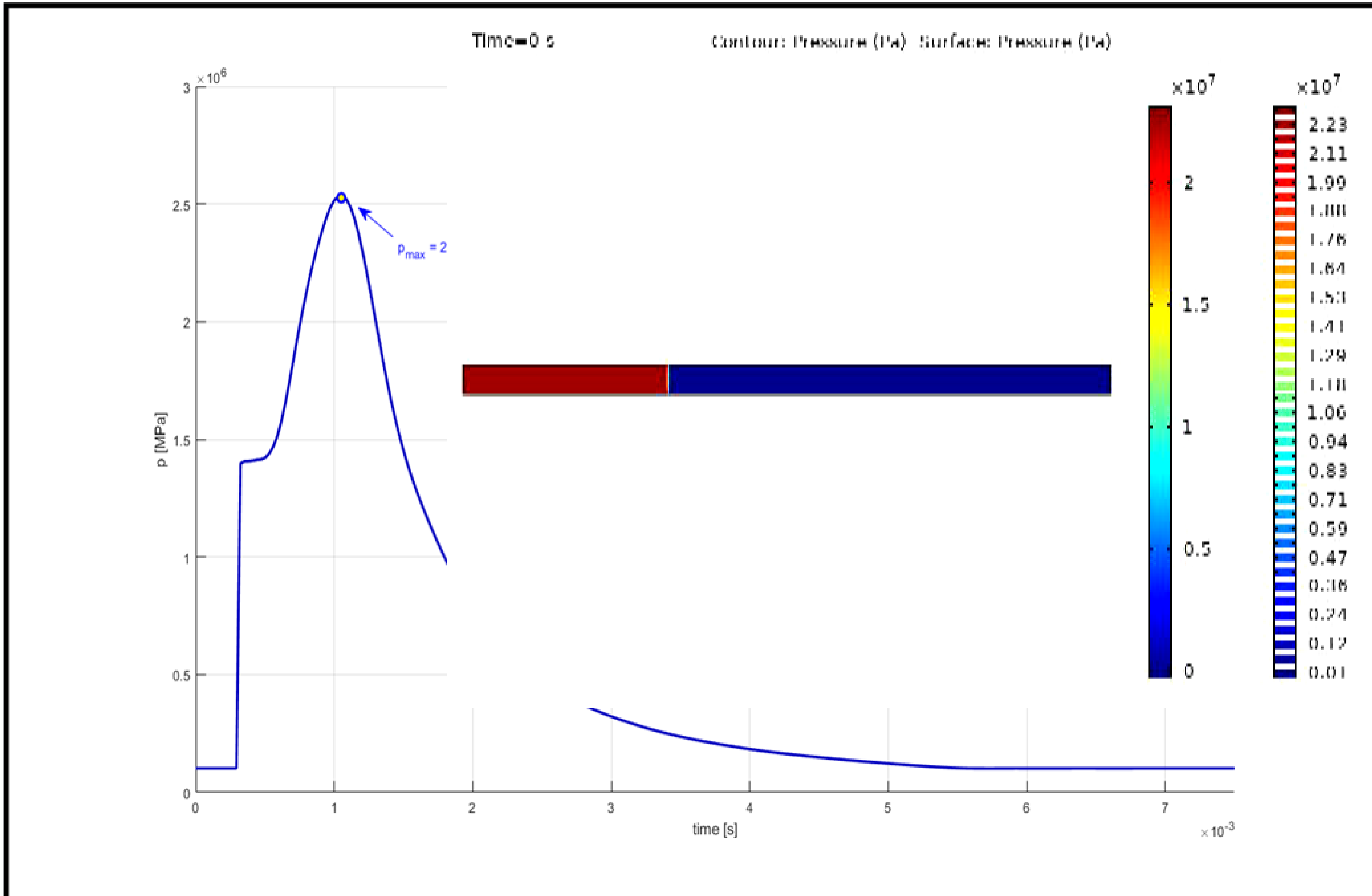
$$u(t_0) = 0 \qquad \frac{\partial u(t_0)}{\partial t} = 0 \qquad p = p_{valve}$$

$$u(t_0) = 0 \qquad \frac{\partial u(t_0)}{\partial t} = 0 \qquad p = p_{env}$$

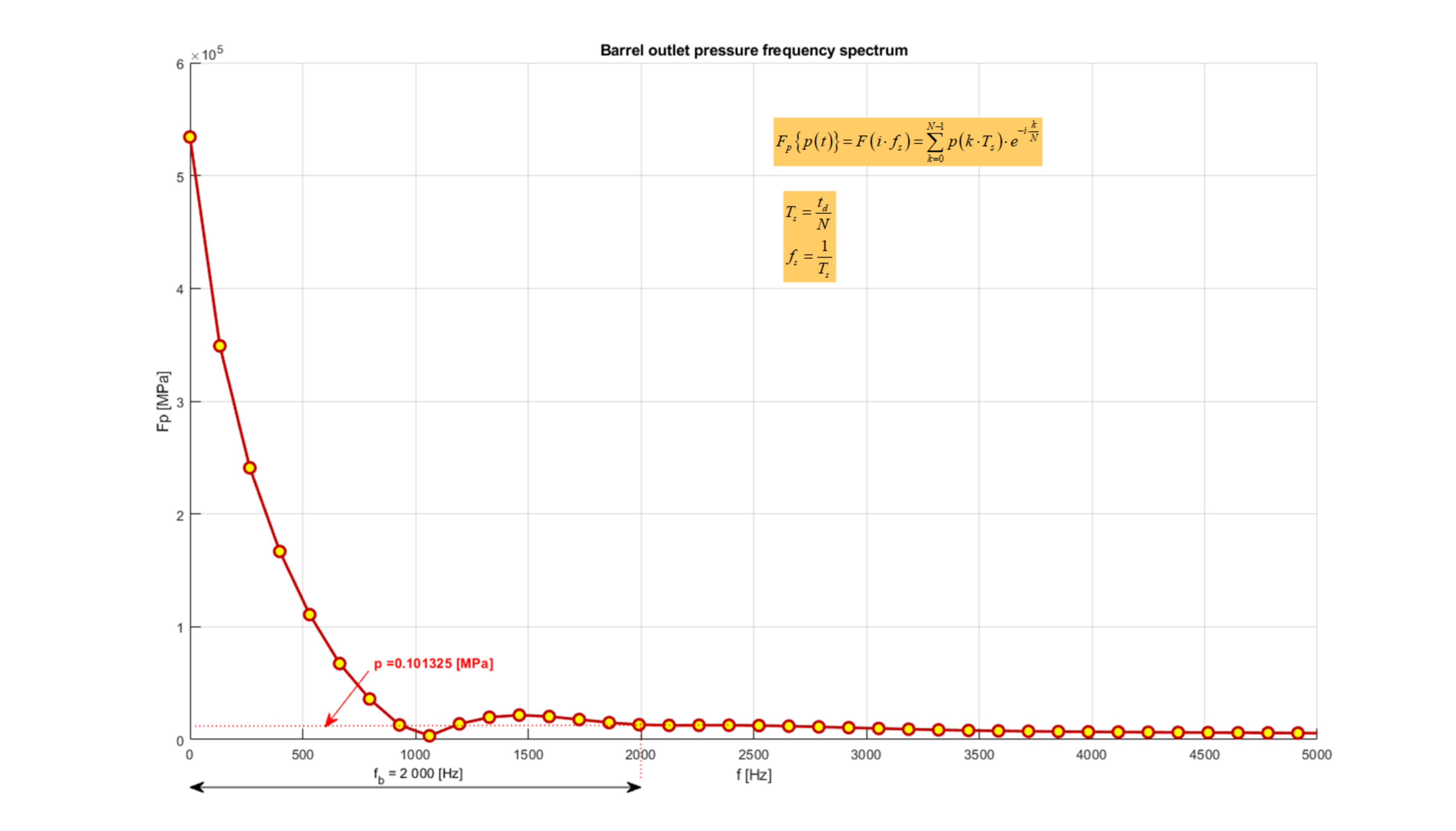
Dynamika pohybu vzduchu ve vzduchovém dělu



Dynamika pohybu vzduchu ve vzduchovém dělu



Dynamika pohybu vzduchu ve vzduchovém dělu



Šíření akustické tlakové vlny v testovací komoře

$$\frac{1}{\rho \cdot v_s^2} \cdot \frac{\partial^2}{\partial t^2} \cdot p + \nabla \cdot \left(\frac{1}{\rho} \cdot \nabla \cdot p \right) = Q_i$$

$$p_t = p + p_b$$

Tlakový puls

$$Q_i = \frac{1}{\rho \cdot v_s} \cdot \frac{\partial p}{\partial t} + n \cdot \frac{1}{\rho} \cdot \nabla \cdot p(t)$$

$$p_i = p_0 \cdot G(r,t) \cdot \sin\left(2 \cdot \pi \cdot f_{max} \cdot \left(t - \frac{(r \cdot e_k)}{v_s \cdot |e_k|} \right) \right)$$

$$G(r,t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{\left(t - 4 \cdot \sigma - \frac{((r - r_0) \cdot e_k)}{v_s \cdot |e_k|} \right)^2}{2 \cdot \sigma} \right)$$

$$\sigma = \frac{\sqrt{\ln(2)}}{\pi \cdot f_b}$$

Šíření rovinné vlny

$$-n \cdot \left(-\frac{1}{\rho} \cdot (\nabla \cdot p - q_d) + \frac{1}{\rho \cdot v_s} \cdot \frac{\partial p}{\partial t} \right) = Q_m$$

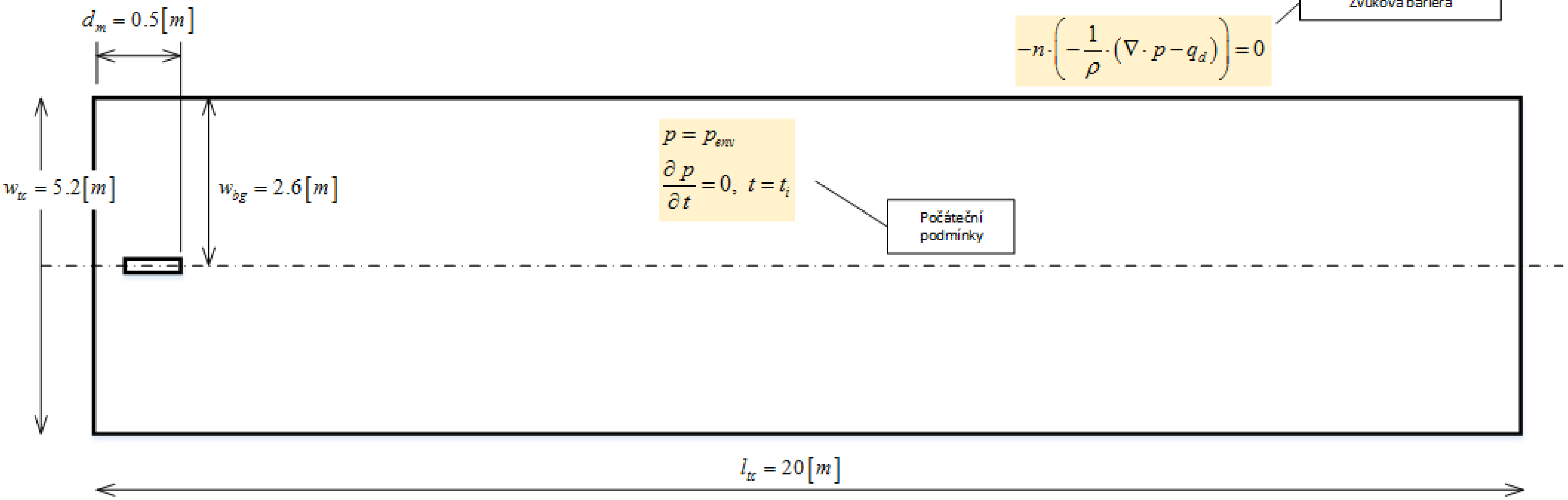
Zvuková bariera

$$-n \cdot \left(-\frac{1}{\rho} \cdot (\nabla \cdot p - q_d) \right) = 0$$

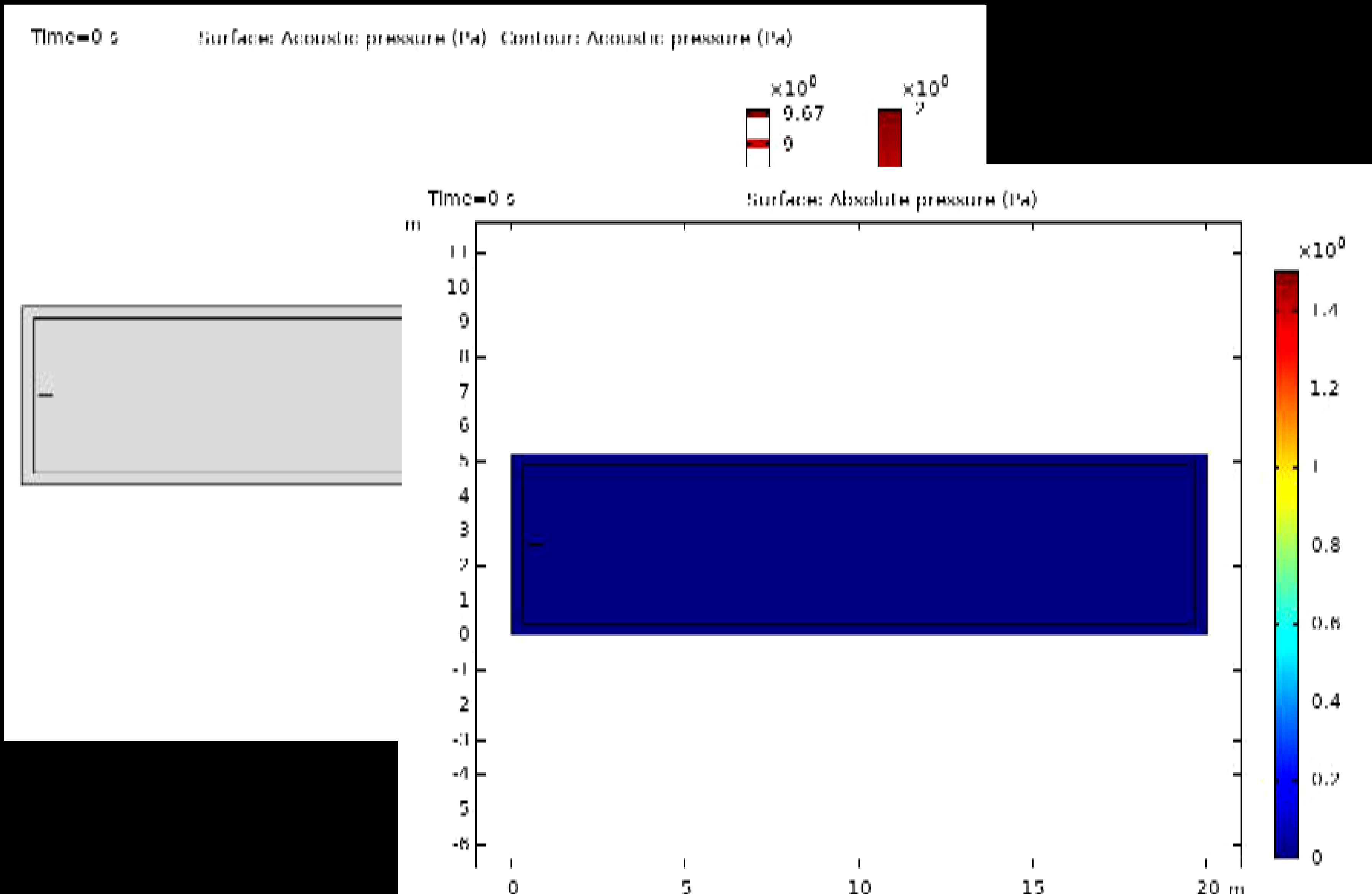
Počáteční podmínky

$$p = p_{env}$$

$$\frac{\partial p}{\partial t} = 0, \ t = t_i$$



Šíření akustické tlakové vlny v testovací komoře



Permitivita prostředí

$$n = \frac{c}{v} = \sqrt{\frac{\varepsilon \cdot \mu}{\varepsilon_0 \cdot \mu_0}} = \sqrt{\varepsilon_r \cdot \mu_r}$$

$$\mu = \mu_r \cdot \mu_0,\ \mu_0 = 4 \cdot \pi \cdot 10^{-7}$$

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0,\ \varepsilon_0 = \frac{625000}{22468879468420441 \cdot \pi}$$

$$\varepsilon_r = \frac{n^2}{\mu_r} = \frac{\left(N \cdot 10^{-6} + 1\right)^2}{\mu_r}$$

$$\mu_r = 1$$

$$N = K_1 \cdot \left(\frac{p_d}{T}\right) + K_2 \cdot \left(\frac{p_w}{T}\right) + K_3 \cdot \left(\frac{p_w}{T^2}\right)$$

$$p_d = p - p_w$$

$$n = N \cdot 10^{-6} + 1$$

$$K_1 = 0.776 \left[\frac{K}{Pa}\right]$$

$$K_2 = 0.72 \left[\frac{K}{Pa}\right]$$

$$K_3 = 3.76 \cdot 10^3 \left[\frac{K^2}{Pa}\right]$$

Empirické parametry

Ernest K. Smith, Jr., Stanley Weintraub.
The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies
Journal of Research of the Notional Bureau of Standards, 1953

$$p_d \cdot V = m_d \cdot R_d \cdot T$$

$$p_w \cdot V = m_w \cdot R_w \cdot T$$

$$\xi = \frac{m_d}{m_w} = \frac{R_w}{R_d} \cdot \frac{p_w}{p - p_w}$$

Specifická plynová konstanta vodní páry

Specifická plynová konstanta suchého vzduchu

$$R_d = 287.11 \left[J/(kg \cdot K)\right]$$

$$R_w = 461.5 \left[J/(kg \cdot K)\right]$$

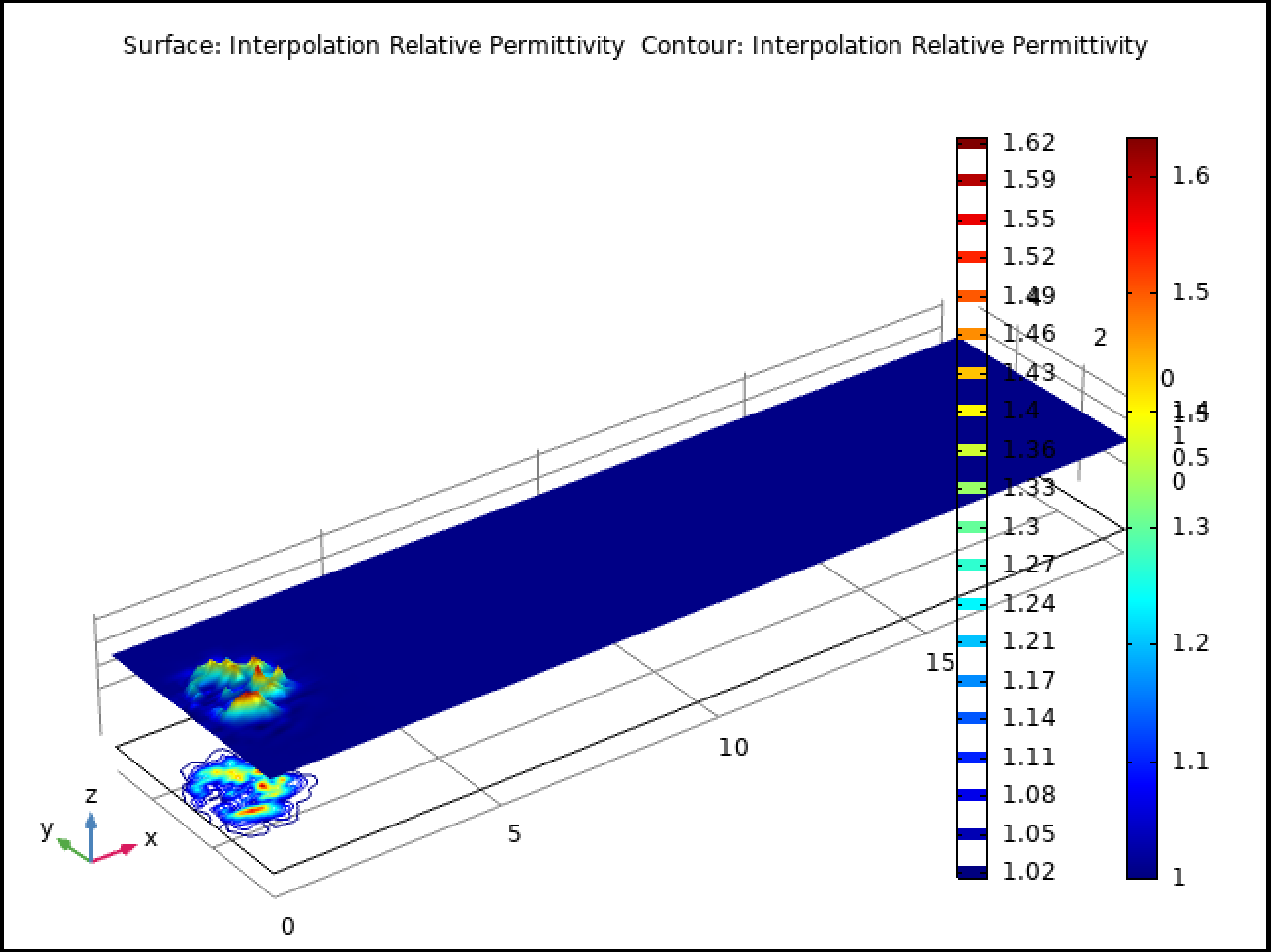
Specifická plynová konstanta vodní páry

$$\varepsilon_r = \left(N \cdot 10^{-6} + 1\right)^2$$

$$N = K_1 \cdot \left(\frac{p - p_w}{T}\right) + K_2 \cdot \left(\frac{p_w}{T}\right) + K_3 \cdot \left(\frac{p_w}{T^2}\right)$$

$$p_w = \xi \cdot \frac{p \cdot R_d}{R_w + \xi \cdot R_d}$$

Permitivita prostředí



Elektromagnetické pole v testovací komoře

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = \rho_q$$

$$B = \mu \cdot H$$

$$D = \varepsilon \cdot E$$

$$J = \sigma \cdot E$$

$$\mu = \mu_r \cdot \mu_0,\ \mu_0 = 4 \cdot \pi \cdot 10^{-7}$$

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0,\ \varepsilon_0 = 8.854 \cdot 10^{-12}$$

$$\nabla \times E(r) = -i \cdot \omega \cdot \mu \cdot H(r)$$

$$\nabla \times H(r) = i \cdot \omega \cdot \varepsilon \cdot E(r)$$

$$\nabla \times \nabla \times E(r) = -i \cdot \omega \cdot \mu \cdot (\nabla \times H(r))$$

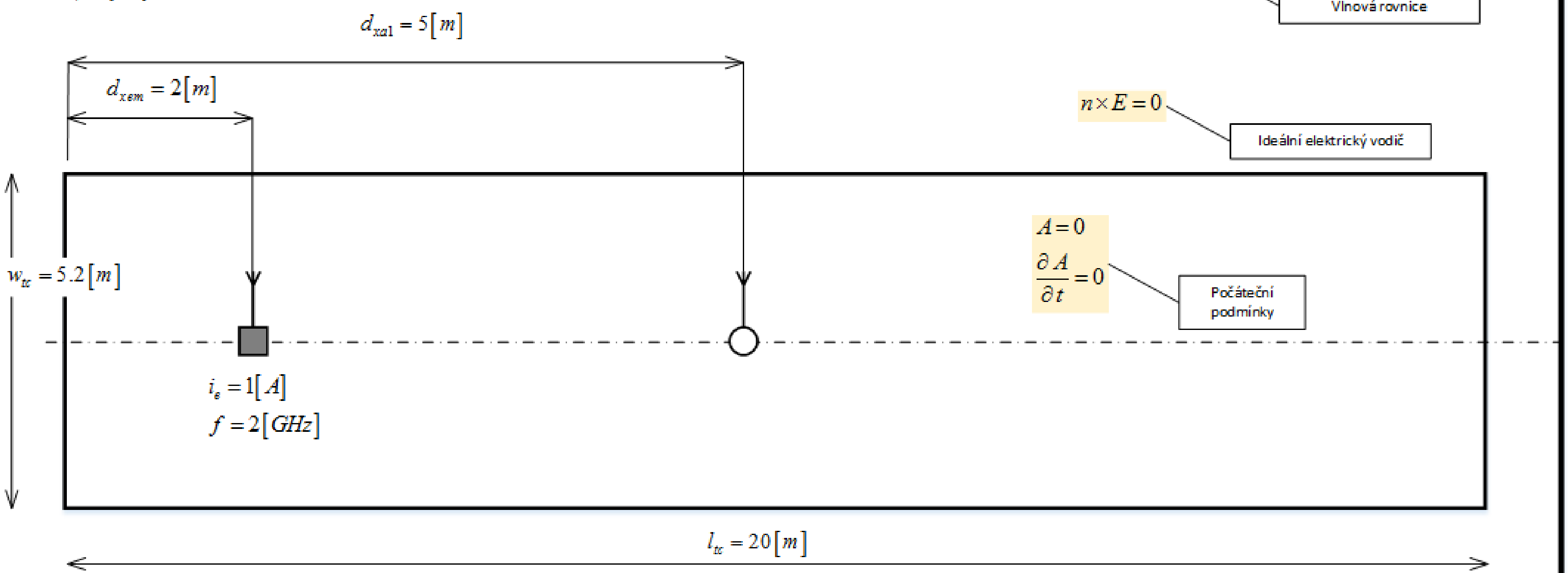
$$\nabla \times \nabla \times E(r) = -i \cdot \omega \cdot \mu \cdot (i \cdot \omega \cdot \varepsilon \cdot E(r))$$

$$\nabla \times \nabla \times E(r) = \omega^2 \cdot \mu \cdot \varepsilon \cdot E(r)$$

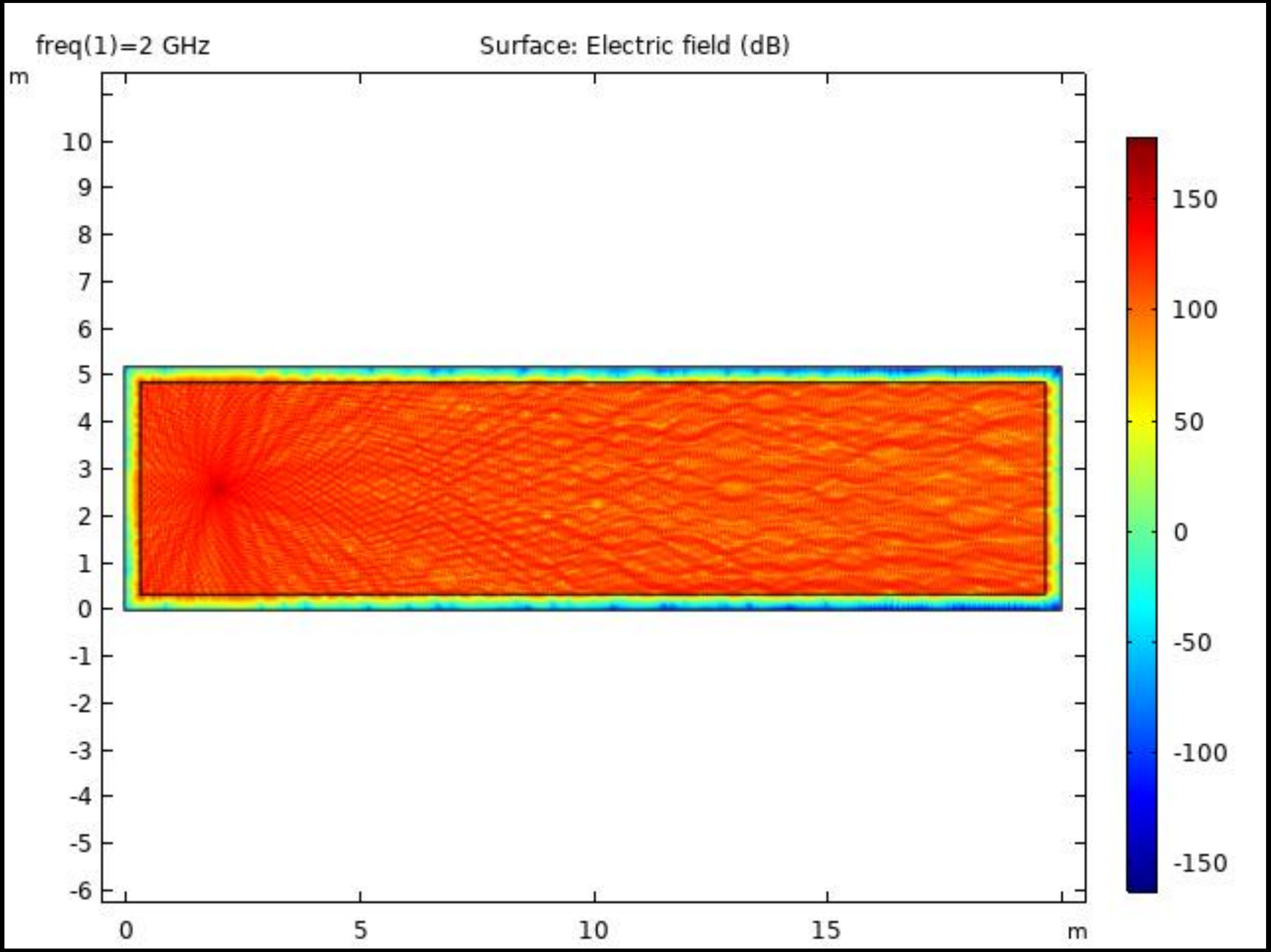
$$k_0 = \omega \cdot \sqrt{\mu \cdot \varepsilon}$$

$$\nabla \times \nabla \times E(r) = k_0^2 \cdot E(r)$$

Vlnová rovnice



Elektromagnetické pole v testovací komoře



Šíření elektromagnetické vlny v testovací komoře

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = \rho_q$$

$$B = \mu \cdot H$$

$$D = \varepsilon \cdot E$$

$$J = \sigma \cdot E$$

$$\mu = \mu_r \cdot \mu_0,\ \mu_0 = 4 \cdot \pi \cdot 10^{-7}$$

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0,\ \varepsilon_0 = 8.854 \cdot 10^{-12}$$

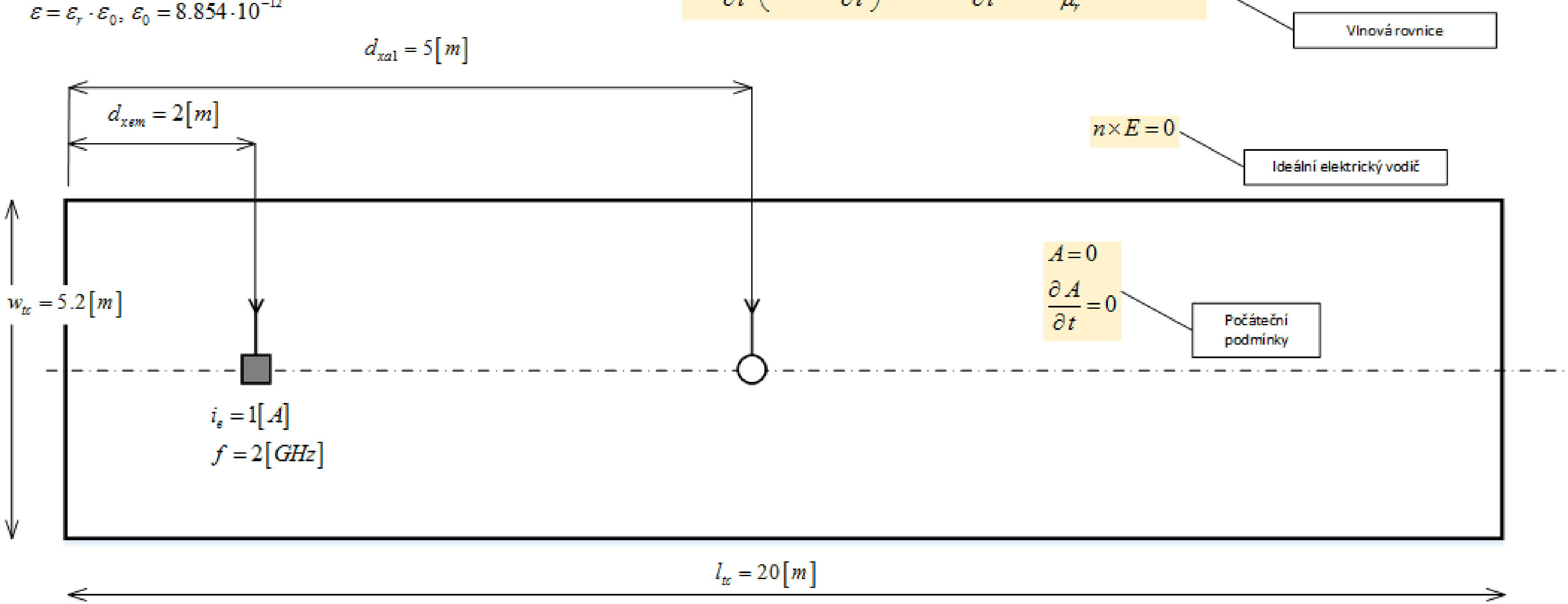
$$\nabla \times \nabla \times E = -\varepsilon \cdot \mu \cdot \frac{\partial^2 E}{\partial t^2} + \frac{1}{\varepsilon} \cdot \frac{\partial J}{\partial t}$$

$$\nabla \times \nabla \times B = -\mu \cdot \varepsilon \cdot \frac{\partial^2 B}{\partial t^2} + \mu \cdot \nabla \times J$$

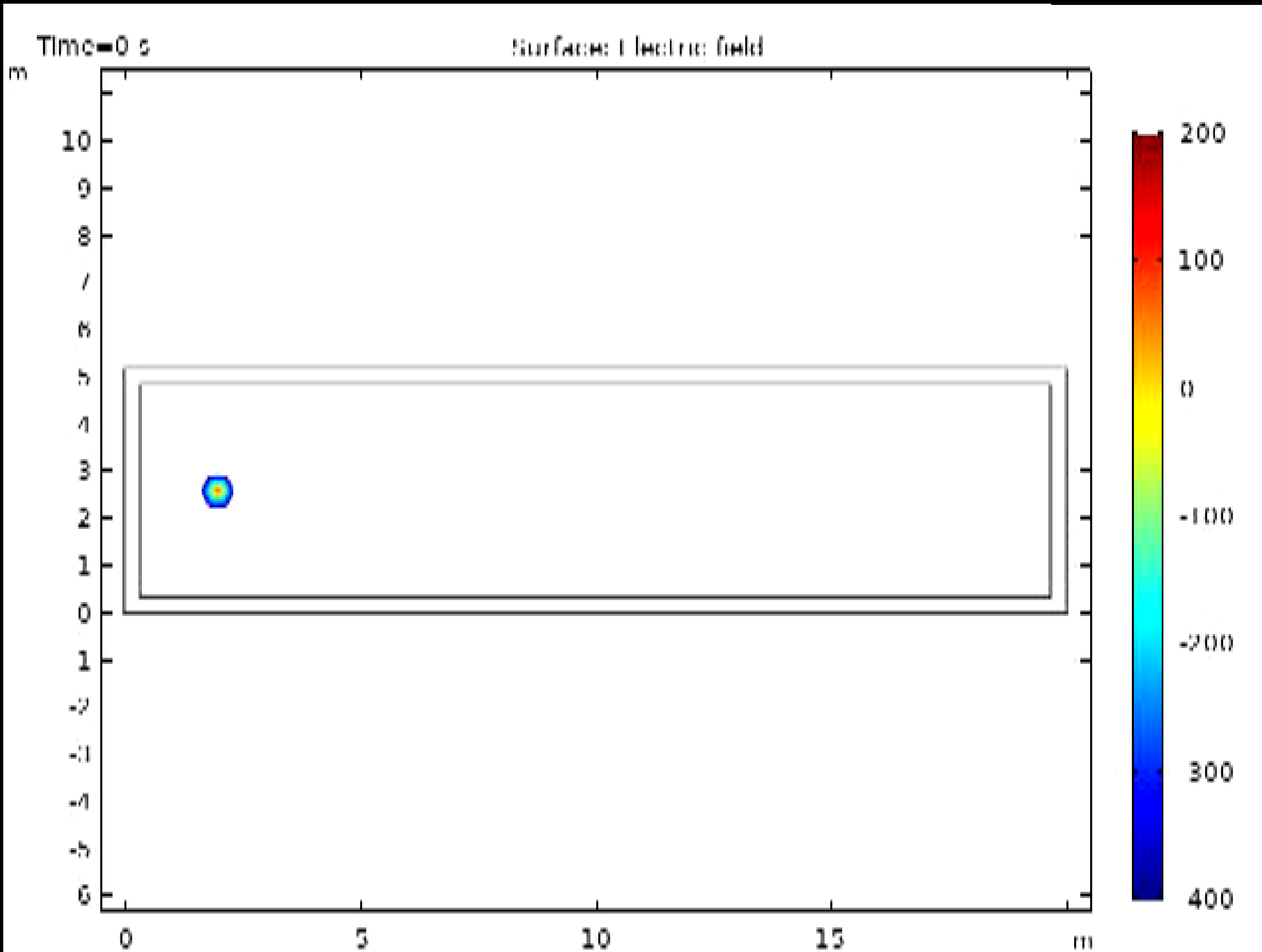
$$\mu_0 \cdot \frac{\partial}{\partial t}\left(\varepsilon_0 \cdot \varepsilon_r \cdot \frac{\partial A_m}{\partial t}\right) + \mu_0 \cdot \sigma \cdot \frac{\partial A_m}{\partial t} + \nabla \times \frac{1}{\mu_r} \cdot (\nabla \times A_m) = 0$$

$$B = \nabla \times A_m$$

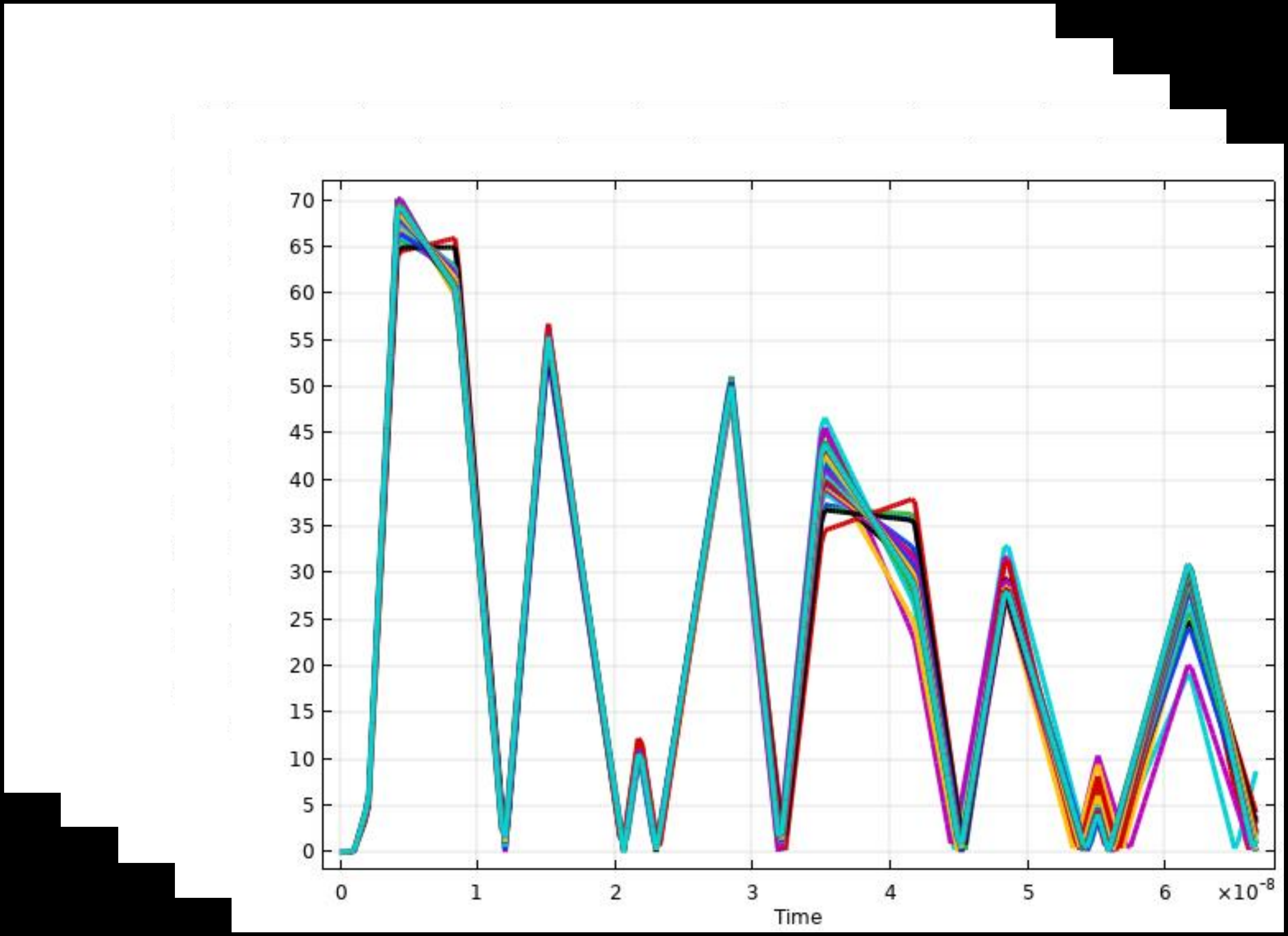
$$\mu_0 \cdot \frac{\partial}{\partial t} \cdot \left(\varepsilon_0 \cdot \varepsilon_r \cdot \frac{\partial A}{\partial t}\right) + \mu_0 \cdot \sigma \cdot \frac{\partial A}{\partial t} + \nabla \times \frac{1}{\mu_r} \cdot (\nabla \times A) = 0$$



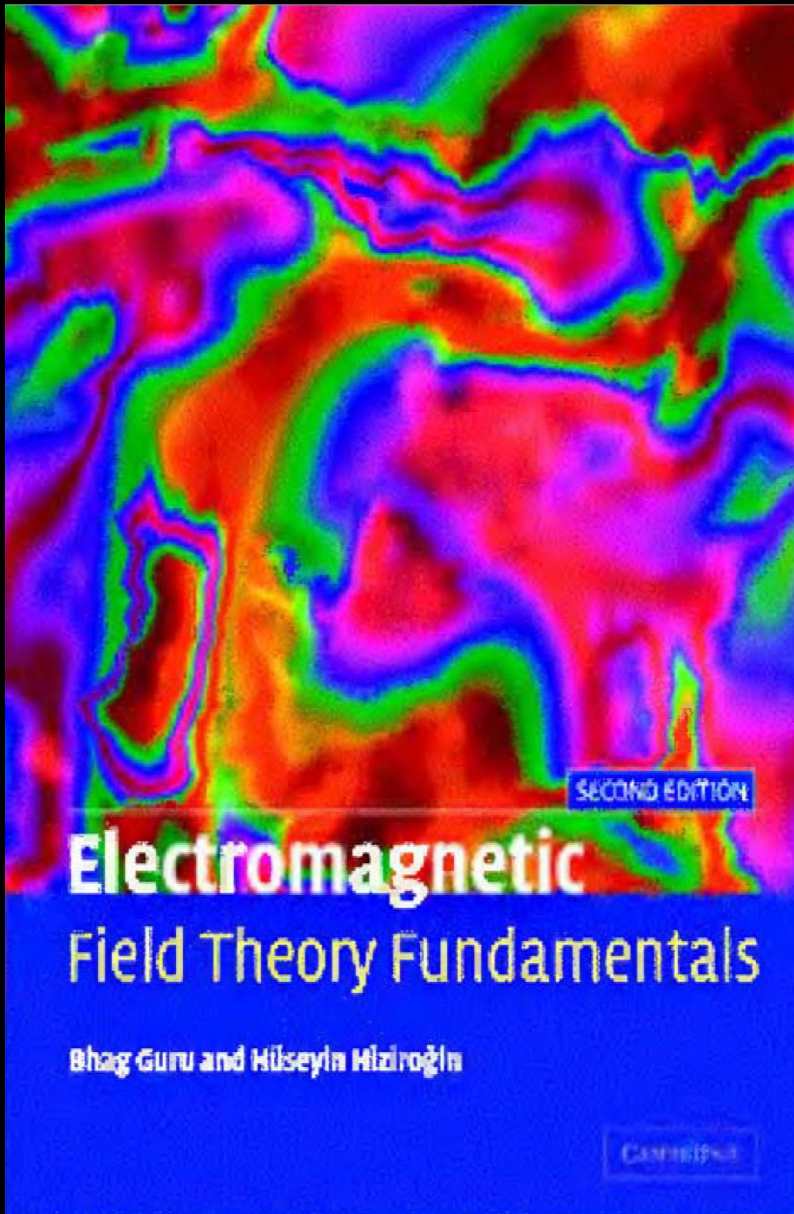
Šíření elektromagnetické vlny v testovací komoře



Šíření elektromagnetické vlny v testovací komoře



Literatura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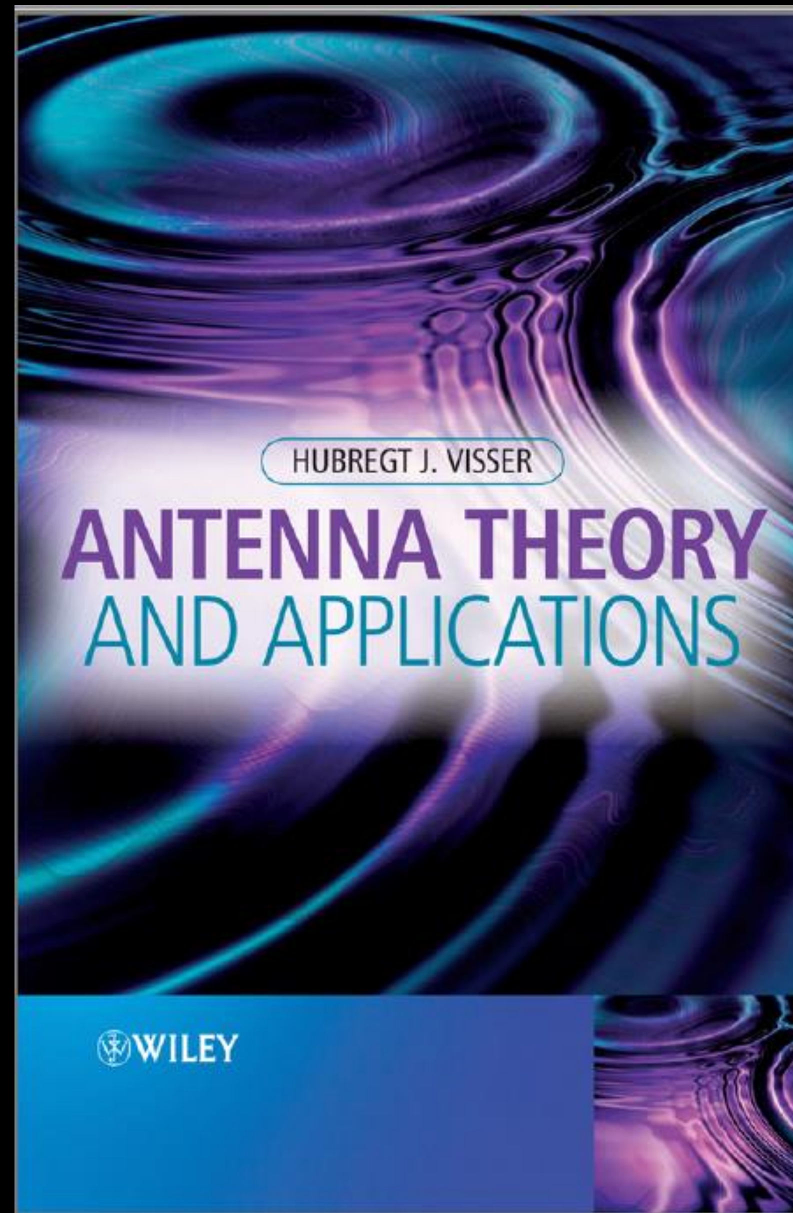
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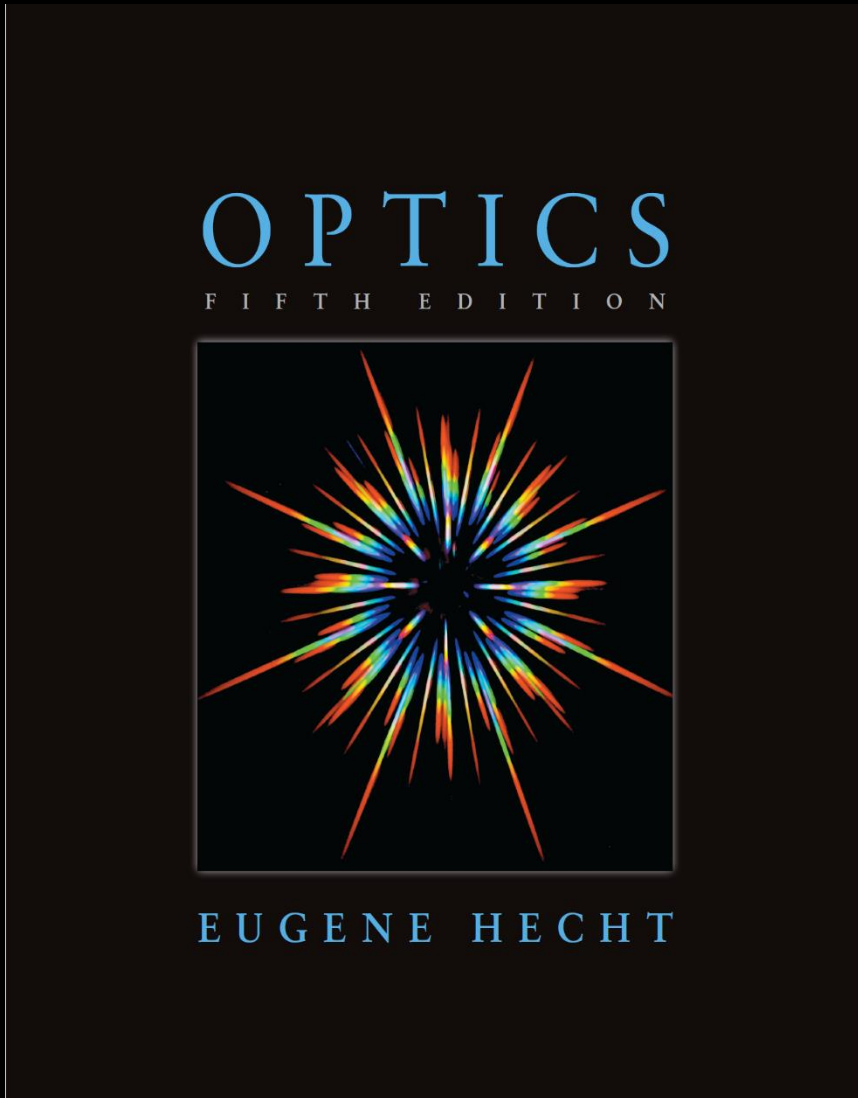

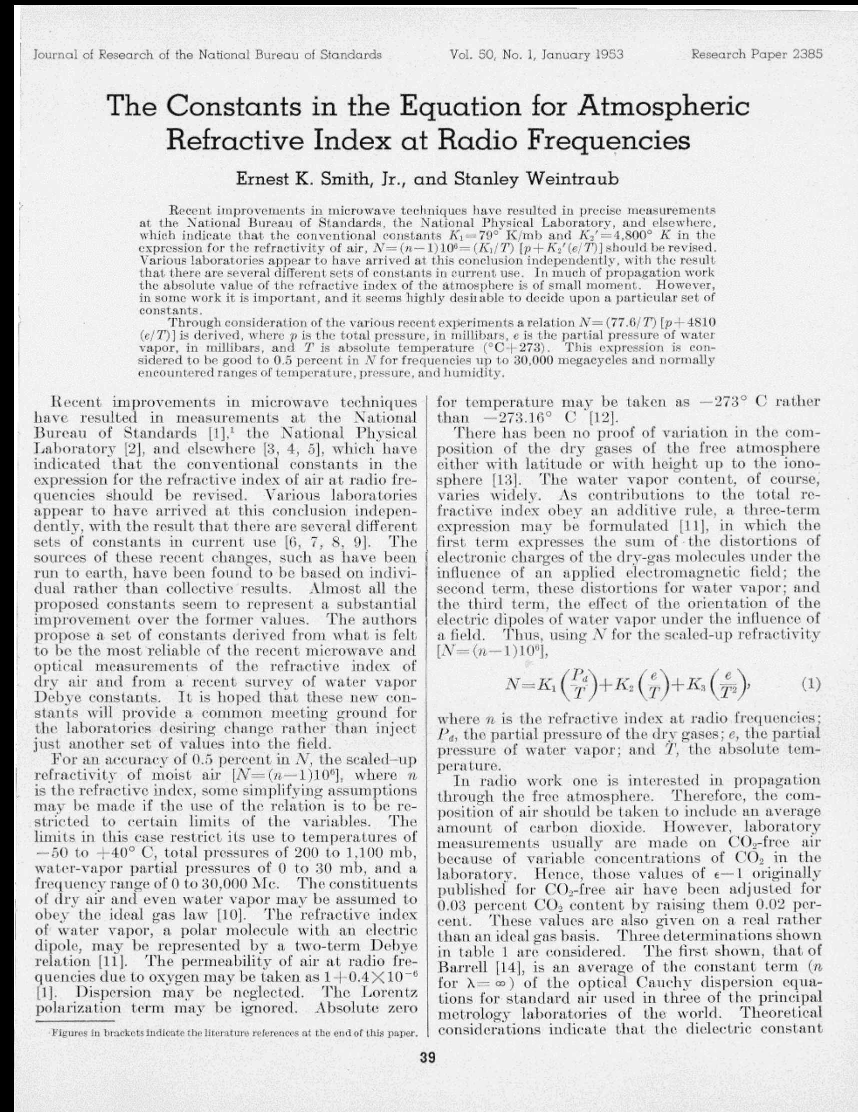
Journal of Research of the National Bureau of Standards Vol. 50, No. 1, January 1953 Research Paper 2385

The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies

Ernest K. Smith, Jr., and Stanley Weintraub

Recent improvements in microwave techniques have resulted in precise measurements at the National Bureau of Standards, the National Physical Laboratory, and elsewhere, which indicate that the conventional constants $K_1=79°$ K/mb and $K_2'=4{,}800°$ K in the expression for the refractivity of air, $N=(n-1)10^6=(K_1/T)\,[p+K_2'(e/T)]$ should be revised. Various laboratories appear to have arrived at this conclusion independently, with the result that there are several different sets of constants in current use. In much of propagation work the absolute value of the refractive index of the atmosphere is of small moment. However, in some work it is important, and it seems highly desirable to decide upon a particular set of constants.

Through consideration of the various recent experiments a relation $N=(77.6/T)\,[p+4810\,(e/T)]$ is derived, where p is the total pressure, in millibars, e is the partial pressure of water vapor, in millibars, and T is absolute temperature (°C+273). This expression is considered to be good to 0.5 percent in N for frequencies up to 30,000 megacycles and normally encountered ranges of temperature, pressure, and humidity.

Recent improvements in microwave techniques have resulted in measurements at the National Bureau of Standards [1],[1] the National Physical Laboratory [2], and elsewhere [3, 4, 5], which have indicated that the conventional constants in the expression for the refractive index of air at radio frequencies should be revised. Various laboratories appear to have arrived at this conclusion independently, with the result that there are several different sets of constants in current use [6, 7, 8, 9]. The sources of these recent changes, such as have been run to earth, have been found to be based on individual rather than collective results. Almost all the proposed constants seem to represent a substantial improvement over the former values. The authors propose a set of constants derived from what is felt to be the most reliable of the recent microwave and optical measurements of the refractive index of dry air and from a recent survey of water vapor Debye constants. It is hoped that these new constants will provide a common meeting ground for the laboratories desiring change rather than inject just another set of values into the field.

For an accuracy of 0.5 percent in N, the scaled-up refractivity of moist air $[N=(n-1)10^6]$, where n is the refractive index, some simplifying assumptions may be made if the use of the relation is to be restricted to certain limits of the variables. The limits in this case restrict its use to temperatures of -50 to $+40°$ C, total pressures of 200 to 1,100 mb, water-vapor partial pressures of 0 to 30 mb, and a frequency range of 0 to 30,000 Mc. The constituents of dry air and even water vapor may be assumed to obey the ideal gas law [10]. The refractive index of water vapor, a polar molecule with an electric dipole, may be represented by a two-term Debye relation [11]. The permeability of air at radio frequencies due to oxygen may be taken as $1+0.4\times10^{-6}$ [1]. Dispersion may be neglected. The Lorentz polarization term may be ignored. Absolute zero for temperature may be taken as $-273°$ C rather than $-273.16°$ C [12].

There has been no proof of variation in the composition of the dry gases of the free atmosphere either with latitude or with height up to the ionosphere [13]. The water vapor content, of course, varies widely. As contributions to the total refractive index obey an additive rule, a three-term expression may be formulated [11], in which the first term expresses the sum of the distortions of electronic charges of the dry-gas molecules under the influence of an applied electromagnetic field; the second term, these distortions for water vapor; and the third term, the effect of the orientation of the electric dipoles of water vapor under the influence of a field. Thus, using N for the scaled-up refractivity $[N=(n-1)10^6]$,

$$N=K_1\left(\frac{P_d}{T}\right)+K_2\left(\frac{e}{T}\right)+K_3\left(\frac{e}{T^2}\right), \qquad (1)$$

where n is the refractive index at radio frequencies; P_d, the partial pressure of the dry gases; e, the partial pressure of water vapor; and T, the absolute temperature.

In radio work one is interested in propagation through the free atmosphere. Therefore, the composition of air should be taken to include an average amount of carbon dioxide. However, laboratory measurements usually are made on CO_2-free air because of variable concentrations of CO_2 in the laboratory. Hence, those values of $\epsilon-1$ originally published for CO_2-free air have been adjusted for 0.03 percent CO_2 content by raising them 0.02 percent. These values are also given on a real rather than an ideal gas basis. Three determinations shown in table 1 are considered. The first shown, that of Barrell [14], is an average of the constant term (n for $\lambda=\infty$) of the optical Cauchy dispersion equations for standard air used in three of the principal metrology laboratories of the world. Theoretical considerations indicate that the dielectric constant

[1] Figures in brackets indicate the literature references at the end of this paper.

Děkuji za pozornost