REFLECTION AND SCATTERING OF ACOUSTIC WAVES IN THE SOLAR ATMOSPHERE

S. N. Osipov

Main Astronomical Observatory, NAS of Ukraine
27 Zabolotnoho St., 03680 Kyiv, Ukraine
e-mail: osipov@mao.kiev.ua

The reflection and transmission complex coefficients for various heights are calculated for MACKKL model of the solar atmosphere for approximation of the isothermal solar atmosphere stratified by gravitation. The anomalous behaviour of amplitude and phase of reflected and transmitted waves along acoustic cut-off frequency line in height-frequency diagram and reflection phase jump at temperature minimum height are shown. The simulation of primary upward velocity wave and superposition fields of velocities of the reflected and scattered waves at different layers are carried out. For the chromosphere the superposed reflected and scattered velocity fields demonstrate the negative phase dependence as the primary upward velocity wave.

INTRODUCTION

The reflection of acoustic waves was considered for the first time by Mein and Mein [4] to account for standing waves pattern in the solar chromosphere. The reflection conditions for the isothermal atmosphere were analyzed in [3, 2]. At the discontinuity between uniform temperature layers the wave motion must satisfy pressure and velocity continuities. The frequency dependence of reflection coefficients have been studied by a number of authors (*e.g.*, [2, 5]). However, the height dependence of reflection and transmission are known more worse. Moreover, the effects of compound superposition of waves reflected at different heights were not studied. Our goal was, therefore, to study the amplitude and phase behaviour of downward reflected wave fields.

REFLECTION COEFFICIENTS AND REFLECTED WAVES SIMULATION

We have computed the reflection (R) and transmission (T) complex coefficients for various heights for the MACKKL model of the solar atmosphere [1] by using equations derived in [2]. The vertical wavenumber k_z and radiative decay time were calculated according to [6] and [7], respectively.

The reflection and transmission coefficients demonstrate the anomalous behaviour of the amplitude and phase at acoustic cut-off frequency. The reflection phase jump at the temperature minimum height is confirmed. There is a difference in the above coefficients for various directions of propagation.

The analytic form for the simulation of monochromatic plane stationary wave propagation is known (*e.g.*, [3]). Such an expression for a wave reflected at the fixed height is known as well [2]. We consider the superposition of waves partially reflected at different heights. Therefore, the downward velocity can be written as

$$V_z^{dn} = V_z^{up} \int\limits_z^{\infty} R_z^{up} \prod_z^{z_r} \left(T_z^{dn} T_z^{up}\right) \exp\left(-2i \int\limits_z^{z_r} k_z dz\right) dz_r, \tag{1}$$

where V_z^{up} is the complex velocity amplitude of the primary upward wave, z is the height of the atmosphere, index up and dn refer to the velocity, reflection and transmission of the upward and downward propagation, respectively.

Moreover, we insert the waves scattering in our speculations. It is necessary to account for the waves, changing the direction of propagation without phase modification. As the first approximation we considered isotropic scattering without height dependence. The approach is very rough, but in such a way we can estimate scattering effects. Eq. (1) adopts to

$$V_z^{dn} = V_z^{up} \int\limits_z^{\infty} G(1 - \frac{5}{6}S)^{2(n_{z_r} - n_z)} \prod_z^{z_r} \left(T_z^{dn} T_z^{up}\right) \exp\left(-2i \int\limits_z^{z_r} k_z dz\right) dz_r, \tag{2}$$

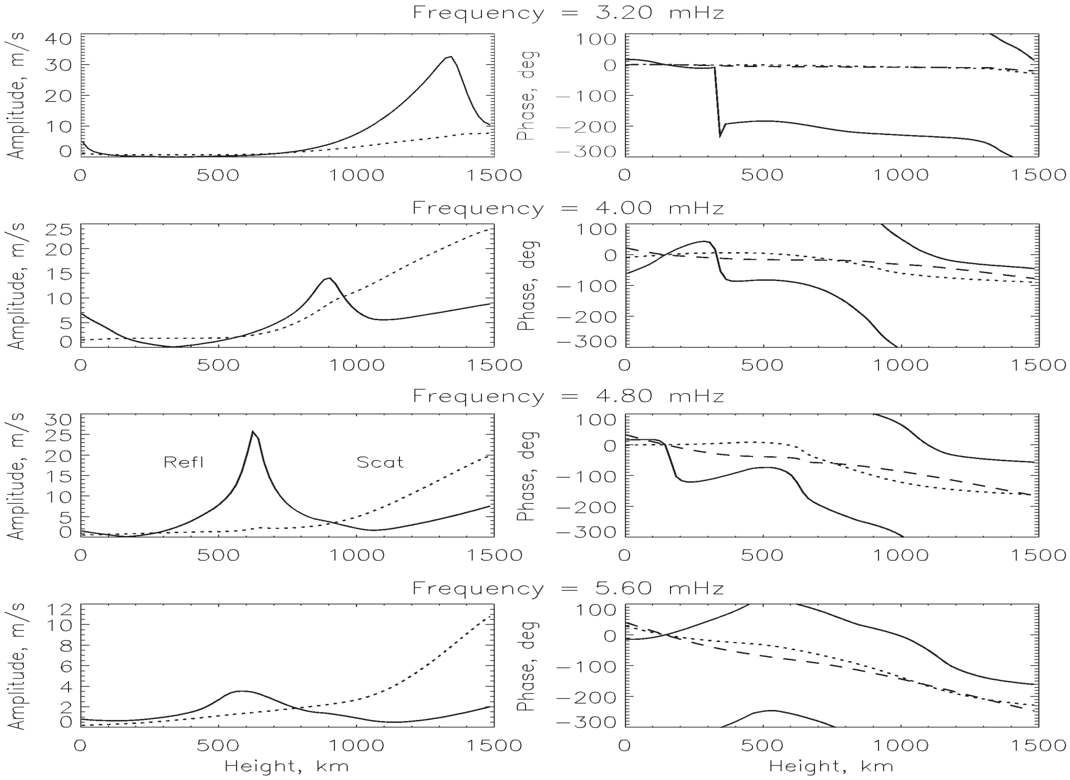

Figure 1: The height dependence of the amplitudes and phases of downward reflected and scattered velocity waves. Solid lines refer to reflected waves, dotted lines to scattered waves and dashed curves to primary upward waves

where G corresponds to R_z^{up} for the reflected waves and corresponds $S/6$ for the scattered waves, S is the scattering coefficient.

Results of numerical simulations are shown in Figure 1. For the chromosphere the superposed reflected and scattered downward velocity fields demonstrate the tendency of negative phase dependence as a primary upward velocity wave V_z^{up}. It is rather unexpectedly because a single wave reflected at any fixed height demonstrates a positive downward phase course. This result may be explained by strong damping of downward waves. Therefore, the reflected wave field phase behaviour is designated by phase of a primary wave at the little higher heights. For the photosphere the phases of the reflected waves are more intricate.

The reflected waves amplitudes has a sharp maxima at layers below the acoustic cut-off frequency heights. The location of the reflected waves phase jump generated at the temperature minimum is reduced with frequency and occurs at heights from 150 to 350 km. The reflected waves amplitudes at these heights are insignificant. The scattered waves mask this jump and prevent the phase jump being observed.

REFERENCES

[1] *Maltby P., Avrett E. H., Carlsson M., et al.* A new sunspot umbral model and its variation with the solar cycle // Astrophys. J.–1986.–**306**, N 1.–P. 284-303.

[2] *Marmolino C., Severino G., Deubner F.-L., et al.* Phases and amplitudes of acoustic-gravity waves II. The effects of reflection // Astron. and Astrophys.–1993.–**278**.–P. 617–626.

[3] *Mihalas D. and Mihalas B. W.* Foundation of Radiation Hydrodynamics.–New York: Oxford Univ., 1984.

[4] *Mein N., Mein P.* Velocity waves in the quiet solar chromosphere // Solar Phys.–1976.–**49**.–P. 231–248.

[5] *Kumar P.* Excitation and Damping of Solar Acoustic Oscillation // Solar Convection and Oscillations and their Relationship / Eds Pijpers F. P., *et al.*–New York, 1997.–P. 161–169.

[6] *Souffrin P.* Hydrodynamics of an Atmosphere Disturbed by a Subjacent Turbulent Convective Zone // Ann. Astrophys.–1966.–**29**.–P. 55–101.

[7] *Spiegel E. A.* The Smoothing of temperature Fluctuations by Radiative Transfer // Astrophys. J.–1957.–**126**.–P. 202–207.