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Wave like fluctuations of the total neutral density of amplitude increasing with altitude in the upper thermosphere

P. Bencze[1], E. Illés-Almár[2]

[1]Geodetic and Geophysical Research Institute, Hungarian Academy of Sciences, H-9401 Sopron, P.O.B. 5, Hungary. E-mail: bencze@ggki.hu
[2]Konkoly Observatory, Hungarian Academy of Sciences, H-1525 Budapest, P.O.B. 67, Hungary. E-mail: illes@konkoly.hu

Abstract

An abrupt change in the amplitude of wave like fluctuations of the total neutral density has been found in measurements of the DBI accelerometer on board of the San Marco V satellite at a certain height between 300 and 500 km in the equatorial region. Considering the temperature variation with height in this region, (that is a vertical temperature gradient decreasing with height) the effect of convective instability has been assumed as an explanation. A study of the behaviour of internal atmospheric gravity waves indicated that gravity wave instability can develop under certain conditions in the atmosphere. However, on the basis of statistical investigations of the observed abrupt changes in amplitude of wave-like total neutral density fluctuations and comparing the data with results of theoretical computations it has been demonstrated that these wave like fluctuations may occur due to convective instability.

Keywords: Wave-like total neutral density fluctuations; Thermospheric temperature profile; Wave induced temperature fluctuations; Convective instability; Gravity wave instability

1. Introduction

A study of the high temporal resolution total neutral density data carried out using measurements of the DBI accelerometer on board of the San Marco V satellite enabled the discovery of some new phenomenon in the equatorial thermosphere: 1.) small scale neutral density depletions (NDDs), 2.) wave like fluctuations of amplitude increasing abruptly with altitude in the total neutral density and 3.) impulse like density increases. Statistical investigations of the small scale density depletions indicated that these might be due to plasma bubbles in the equatorial F region of the ionosphere (Illés-Almár et al., 1998; Bencze et al., 2000; Illés-Almár et al., 2001; Schunk and Demars, 2003). Concerning the abrupt amplitude change between 300 and 500 km in wave-like fluctuations of the total neutral density first a statistical analysis of the density data has been carried out. On the basis of the results it has been suggested that the abrupt amplitude change may be connected with convective instability, as fluctuations of amplitude increasing abruptly with altitude occur without exception when the satellite overran a critical height. In this region the temperature increases exponentially with height and approaches to a limit value, to the so called exospheric temperature, that is the temperature change with height is already very small here (Fig. 1).

Though, the temperature variations corresponding to the density fluctuations are of short time-scale, we should not forget that in this part of the atmosphere there are several heat sources determining the temperature. One of them is absorption of the solar extreme ultraviolet radiation by oxygen molecules. This heat source is decreasing with increasing height because of the reduced concentration of oxygen molecules and diminishing also with increasing latitude due to a decrease of the intensity of the solar extreme ultraviolet radiation. [Energy is also supplied by dissociative recombination (ground electronic state of O_2^+), energetic neutral atoms (ENAs) produced by multiple charge exchange, hot atoms due to simple charge exchange, absorption of wave energy (Schunk and Nagy, 2000)]. Heat is only transported vertically by thermal conduction. Thermal conductivity is high in this region because of the high temperature and small neutral-neutral collision frequency. The quasi isothermal state of the thermosphere above 300-400 km is due to this high heat conductivity. The temperature distribution in the upper thermosphere and thus the conditions of development of convective instability are determined by the above mentioned heat sources. As a consequence of the character of these heat sources the temperature increases with enhanced solar activity.

The quasi isothermal state of the upper thermosphere allows the development of a neutral equilibrium and under such circumstances an infinitesimal temperature perturbation is enough for the formation of an instability. The development of electron density fluctuations of amplitude increasing abruptly with altitude seems less probable in the low latitude upper ionosphere, since on the one hand-though the electron and ion densities decrease with increasing height in the height range in question, the electron and ion temperatures are steadily increasing with altitude and thus, there is no possibilitay for development of a neutral equilibrium state. On the other hand the occurrence frequency of collisions between neutrals and charged particles is small because of the small density. Thus, the possibility of an interaction between the neutral and ionized components of the upper atmosphere-like that in case of plasma bubbles – may be ruled out.

2. Observational data and results

Total neutral density data supplied by the DBI accelerometer on board of the San Marco V satellite were used. The inclination of the orbit of the satellite was 3° with perigee down to 130 km and initial apogee of 600 km. The lower heights were reached only at the end of the satellite's lifetime. Most of the measurements were carried out above 250 km. The data refer to the time between April and December 1988. This time period was the rising phase of solar cycle 22, one year before maximum solar activity. The geomagnetic activity was weak, below Ap=15.

Residuals were investigated as a function of different parameters. Residual means ratio of the measured density to the actual CIRA86 (MSIS86) atmospheric model value.

In Fig. 2 examples of wave like fluctuations in residuals of the total neutral density are presented indicating commencement of the abrupt amplitude increase as the altitude of the satellite (shown in the upper right and bottom left parts of the Figure) reaches a critical level on the ascending part of its orbit. In other cases when the satellite is sinking (shown in the upper left and bottom right parts of the Figure), the amplitude begins to decrease and as the satellite is reaching the critical level the amplitude of the wave like fluctuations diminishes abruptly again. The heights have been determined where the amplitude of the fluctuations begins to increase abruptly on the ascending branches or to the contrary where it begins to decrease on the descending branches.

Investigating the origin of the abrupt amplitude change of wave like fluctuations in the upper thermosphere, first statistical analyses have been carried out to determine temporal and spatial variations of their occurrence heights.

In the San Marco V data of total neutral density measurements altogether 117 cases have been found, when the satellite passed through the height interval 300-500 km, and all 117 cases can be considered as events indicating an abrupt change in the amplitude. The number of cases is limited because on the one hand the acclerometer was not switched on in every revolution, on the other hand, if it worked, the satellite sometimes remained under the critical level. The data base included time [given also in modified Julian day (MJD)] height, local solar time, geomagnetic and geographical latitudes, as well as longitudes, San Marco V total density (ρ) and MSIS86 model density (ρ_o) values (in 10^{-15}gcm^{-3} units), finally the $(\rho-\rho_o)/\rho_o$ data at the hight, where the amplitude of density-fluctuations starts to increase, or decrease abruptly.

The diurnal variation of these heights is plotted in Fig. 3. It can be seen that the commencing altitude seems to be enhanced by day as compared with night values. More nearly, the diurnal variation of this height follows the diurnal variation of temperature in this height region at the equator (e.g. Hedin, 1989). Due to the 8 months lifetime of the satellite, the seasonal variation of the commencing altitude could not be investigated, though an increased value in the summer month June is indicated in accordance with the seasonal variation of temperature (Oliver et al., 1989).(Fig. 4).

3. Method: theoretical background

Concerning the theoretical background of our assumption, investigations have indicated that under certain conditions internal atmospheric gravity wave instability may occur (Johnston, 1967). Thus, as a possibility the wave-like fluctuations of amplitude increasing abruptly with height might be related to the instability of internal gravity waves. Conditions (anomalous case) mentioned above are the inequality

$$\omega_B > \omega_a \tag{1}$$

that is the non-isothermal Brunt-Vaisala frequency ω_B must be greater than the acoustic cut-off frequency ω_a. The non-isothermal Brunt-Vaisala frequency is given by the equation (Beer, 1975)

$$\omega_B^2 = \frac{(\gamma-1)g^2}{c^2} + \frac{g}{c^2}\cdot\frac{\partial c^2}{\partial z} \tag{2}$$

where γ is the ratio of specific heat capacities (specific heats) c_p and c_v, g stands for the gravitational acceleration, c is the speed of sound. The accoustic cut-off frequency is expressed by the formula (Beer, 1975)

$$\omega_a = \frac{\gamma g}{2c} \tag{3}$$

where the speed of sound may be written as c=$(\gamma g H)^{1/2}$. Here H is the pressure scale height H=kT/mg, k is Boltzmann's constant and m is mean mass of the constituents of the neutral atmosphere at the given height. That is, since γ and g do not change significantly with altitude, vertical variation of ω_B and ω_a are determined by T and in the former case also by its vertical gradient. This means that conditions for the development of gravity wave instability are also height dependent.

To study the convective instability origin of abrupt amplitude changes in wave-like fluctuations the conditions for the convective instability have to be investigated. In order to determine the height, where conditions of convective instability are fulfilled, the vertical temperature gradient due to atmospheric waves must be compared with the adiabatic temperature gradient Γ_d (Gossard and Hooke, 1975). Adiabatic state itself is namely neutral equilibrium state (Goody, 1995).

$$\Gamma_d = \frac{g}{c_p} \tag{4}$$

where c_p is the specific heat capacity referring to constant pressure. Assuming in the height range studied an atomic oxygen atmosphere, its value is $c_p = 1.27 \cdot 10^3 Jkg^{-1}K^{-1}$

The acceleration due to gravity has been computed taking into account its change with height

$$g = g_o \frac{1}{\left(1 + \frac{z}{R_E}\right)^2} \tag{5}$$

where z is the height in question and R_E is the Earth's radius. For the generation of unstable conditions, it is necessary that the negative vertical temperature gradientdue to density fluxtuations should be greater than the positive adiabatic temperature gradient.

The vertical temperature gradient related to density fluctuations connected with atmospheric waves has been computed by an equation deduced from logarithmic differential of the expression for pressure in the kinetic gas theory p=knT using the perturbation method. Here k is Boltzmann's constant, n and T are the number density and temperature, respectively. Taking the first-order solution, it has been assumed that zeroth-order terms are much larger, than the respective first-order terms. It has also been considered that derivatives according to altitude of first-order terms are much larger, than differentials of the corresponding zeroth order terms. Thus, the following equation is obtained (Beer, 1975, p. 240)

$$\frac{\partial T_1}{\partial z} = \frac{T_o}{p_o} \cdot \frac{\partial p_1}{\partial z} - \frac{T_o}{\rho_o \cdot} \frac{\partial \rho_1}{\partial z} \tag{6}$$

where T_1,p_1, and ρ_1 are first-order parts of the respective parameters. It can be shown that using the equation of pressure in the kinetic gas theory and the hydrostatic approximation

$$\frac{T_0}{p_0} \frac{\partial p_1}{\partial z} = -\frac{\overline{m}g}{k} \cdot \frac{\rho_1}{\rho_0} = -\frac{\overline{m}g}{k} \cdot \frac{\rho - \rho_0}{\rho_0} \tag{7}$$

where ρ_0 is zeroth order term of the density, $\rho_1 = \rho - \rho_0$ the first-order term of the density, where ρ is the measured density and ρ_0 is the model value of density obtained from the upper atmosphere model MSIS 86, using solar and geomagnetic activity indices ($F_{10.7}$, Ap) referring to the time of the event . $\overline{m}$ is the mean molecular mass and g is acceleration due to gravity.

Using relations applied in derivation of Eq. (6), we get for the second term on the right hand side of Eq. (6)

$$-\frac{T_0}{\rho_0}\cdot\frac{\partial\rho_1}{\partial z}=-T_0\frac{\partial}{\partial z}(\frac{\rho-\rho_0}{\rho_0}) \qquad (8)$$

Thus, we get finally from Eqs. (5), (6) and (7)

$$\frac{\partial T_1}{\partial z}=-\frac{\overline{m}g}{k}\left(\frac{\rho-\rho_0}{\rho_0}\right)-T_0\frac{\partial}{\partial z}\left(\frac{\rho-\rho_0}{\rho_0}\right) \qquad (9)$$

Computations are carried out first selecting events of density fluctuations indicating an abrupt increase of amplitude at a certain height according to local time of their occurrence. Taking $(\rho-\rho_0)/\rho_0$ values determined from measured and model values at the beginning of the height of the abrupt amplitude increase and decrease , respectively included in the data base, mean vertical gradient of $(\rho-\rho_0)/\rho_0$ has been determined. Zeroth-order values of temperature were calculated using the MSIS upper atmosphere model, using solar and geomagnetic indices referring to the time of the event. $\overline{m}=M\cdot m_H$, where M is the mean molecular weight and m_H is the mass of a hydrogen atom. M was calculated with the formula

$$M=18.9-6.45\ [1+\tanh\left(\frac{z-300}{100}\right)]$$

(Beer, 1975), since model web browser results do not include M. Acceleration due to gravity was calculated by means of Eq. (5).

4. Discussion

Considering the diurnal variation of the vertical temperature profile, the temperature gradient reaches the neutral equilibrium state (convective instability condition) at greater altitudes in day-time than by night due to the expansion of the atmosphere (Fig. 1). The computed temperature profiles in Fig. 1 – using CIRA 86 upper atmospheric model – correspond to average solar and geomagnetic activities of the period lasting from April to December 1988.

Concerning the internal atmospheric gravity wave instability, height of the equality $\omega_B=\omega_a$ has been computed with parameters corresponding to average values of these parameters referring to the period between April and December 1988 [CIRA 86 (MSIS 86)]. Its diurnal variation compared with diurnal variation of the altitude, where abrupt change of the amplitude of wave-like fluctuations occurs, shows that the latter is much greater (mostly above 400 km) than the former; that is, the abrupt amplitude change of the fluctuations do not indicate direct relation to the instability of internal atmospheric gravity waves, since gravity wave instability is limited to heights below about 200 km in our case .

Inequality (1) would represent the anomalous state occurring above about 120 km (Midgley and Liemohn, 1966), but only to a height of about 300 km. ω_B decreases more strongly than ω_a because both square of the growing speed of sound in the denominator and the decreasing vertical gradient of the square of sound velocity [Eq.(2)] reduce ω_B more intensively, than ω_a decreases in consequence of the growing speed of sound in the denominator [Eq.(3)]. However, under non anomalous conditions as commencing heights of amplitude increase above about 350-400 km, gravity wave instability might enhance the amplitude of oscillations passing the anomalous regions of the atmosphere below 300 km.

Thus, explanation of the abrupt increase in the amplitude of wave-like fluctuations at a certain height has been attempted by study of the convective instability. It has been assumed that convective instability may occur, if the negative vertical temperature gradient due to atmospheric gravity waves is larger, than the positive adiabatic temperature gradient.

For determination of the height, where the abrupt amplitude increase of density fluctuations occurs, first height variation of the adiabatic temperature gradient has been computed. The adiabatic temperature gradient has been determined by means of Eq. (4), thus, taking into account height dependence of the acceleration due to gravity. In the computation MSIS atmospheric models were used. Variation of the vertical temperature gradient with height produced by atmospheric gravity waves was computed using Eq. (6). Computations were carried out again taking MSIS atmospheric models. According to our concept, height of the abrupt amplitude increase of density fluctuations may be determined by trying to find that altitude, where the vertical temperature gradient due to atmospheric gravity waves and the adiabatic temperature gradient become equal the former decreasing faster, than the latter. It is noted again that the adiabatic lapse rate represents neutral equilibrium conditions. In Fig. 5, diurnal variation of these altitudes are plotted. For comparison, diurnal variation of the height of the observed abrupt amplitude increase (see Fig. 3) is also shown. It is to be noted that the difference between experimentally determined values and heights computed from equations comprising the residuals $(\rho-\rho_0)/\rho_0$ may partly be explained by carrying out computations with mean values of the residuals, which differ from mean values used for determination of the „transitional" height; that is, composition of the samples was different. It may be seen that computed values follow quite well the variation of heights obtained from measured data. The height difference between the computed and experimentally determined values is also due to the approximate character of the computations.

5. Summary

As a result of the investigation related to the abrupt amplitude increase of neutral density fluctuations at a certain height, the conclusion can be drawn that this phenomenon might be due to convective instability that would develop above the altitude, where the negative vertical temperature gradient produced by atmospheric gravity waves exceeds the positive adiabatic temperature gradient.

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Figure captions

Fig. 1. Variation of the temperature with height by day (thick line) and at night (thin line).

Fig. 2. Examples of observed total neutral density fluctuations (in the lower part of each example DBI accelerometric measurements, San Marco V satellite) their amplitude indicating an abrupt increase as the height h of the satellite (upper part) reaches certain altitude and abrutply decreasing as the satellite sinks below this altitude.

Fig. 3. Diurnal variation of the height, where abrupt increase of the amplitude of neutral density fluctuations occurs.

Fig. 4. Seasonal variation of the height, where abrupt amplitude increase of the neutral density fluctuations is observed.

Fig. 5. Diurnal variation of the height of abrupt increase of the ampltiude fluctuations determined by computing that altitude, where the positive adiabatic lapse rate equals the negative vertical temperature gradient related to atmospheric gravity waves (quadrangles) indicating commencement of the convective instability. Diurnal variation of the height of observed abrupt amplitude increase of neutral density fluctuations (diamonds) is also shown.

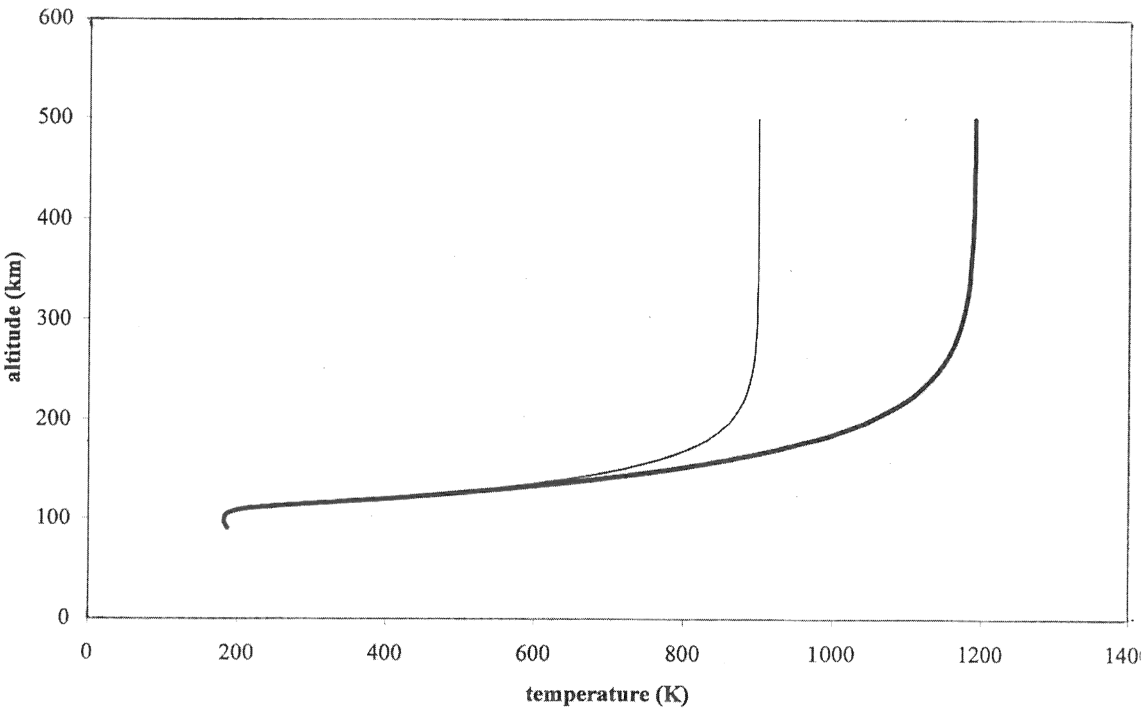

Fig. 1.

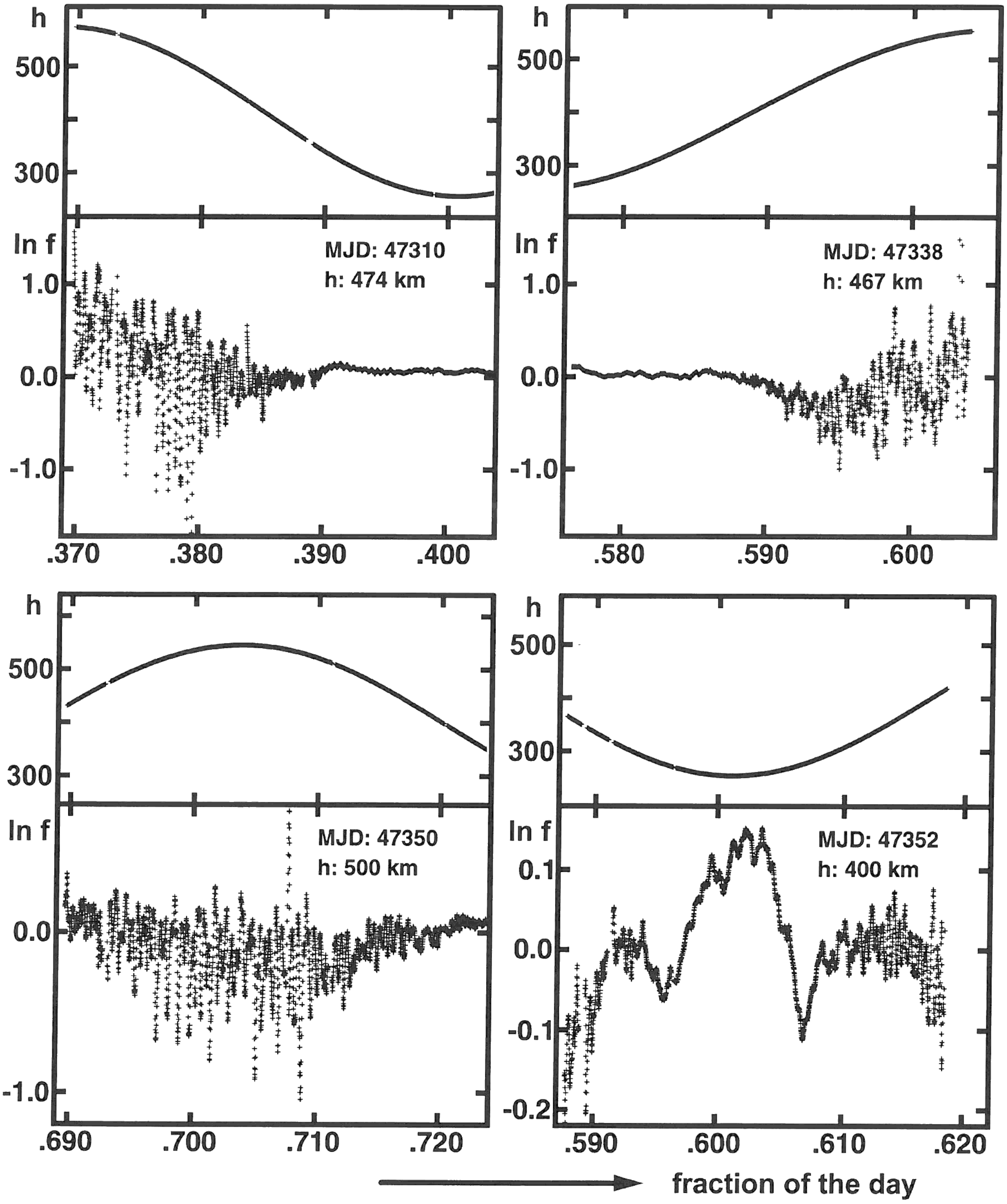
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Fig. 2.

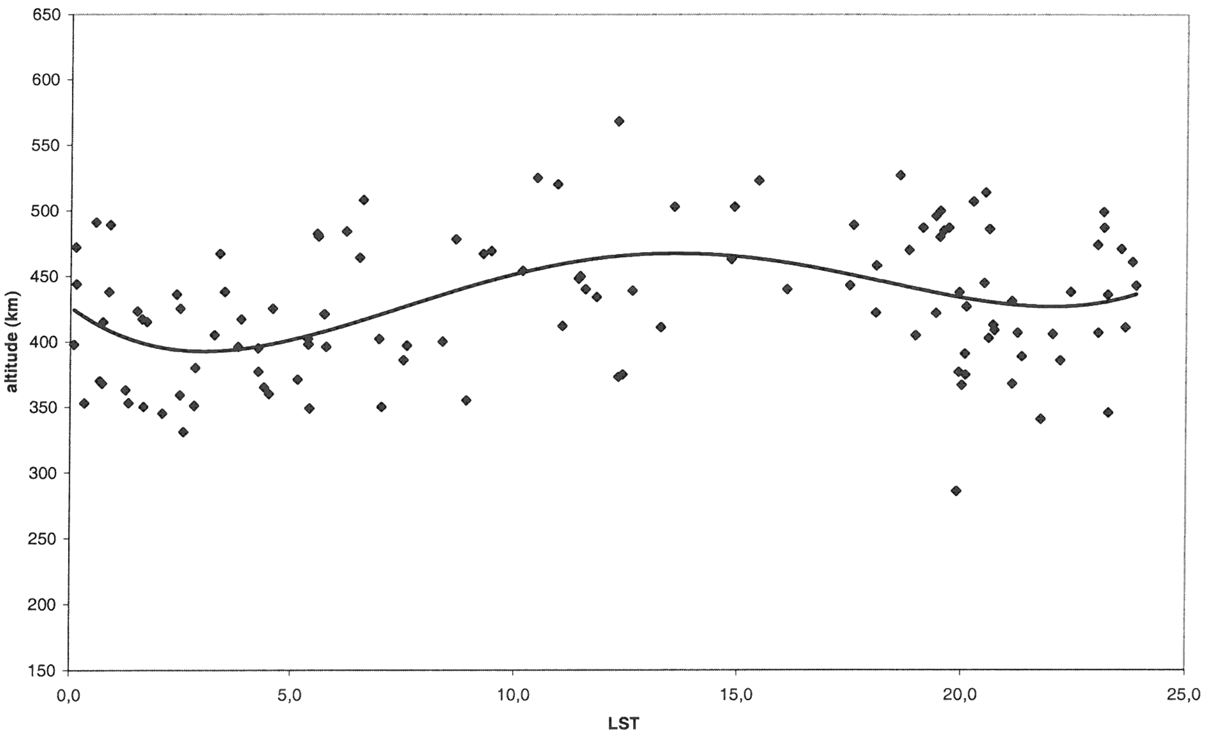
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Fig.3.

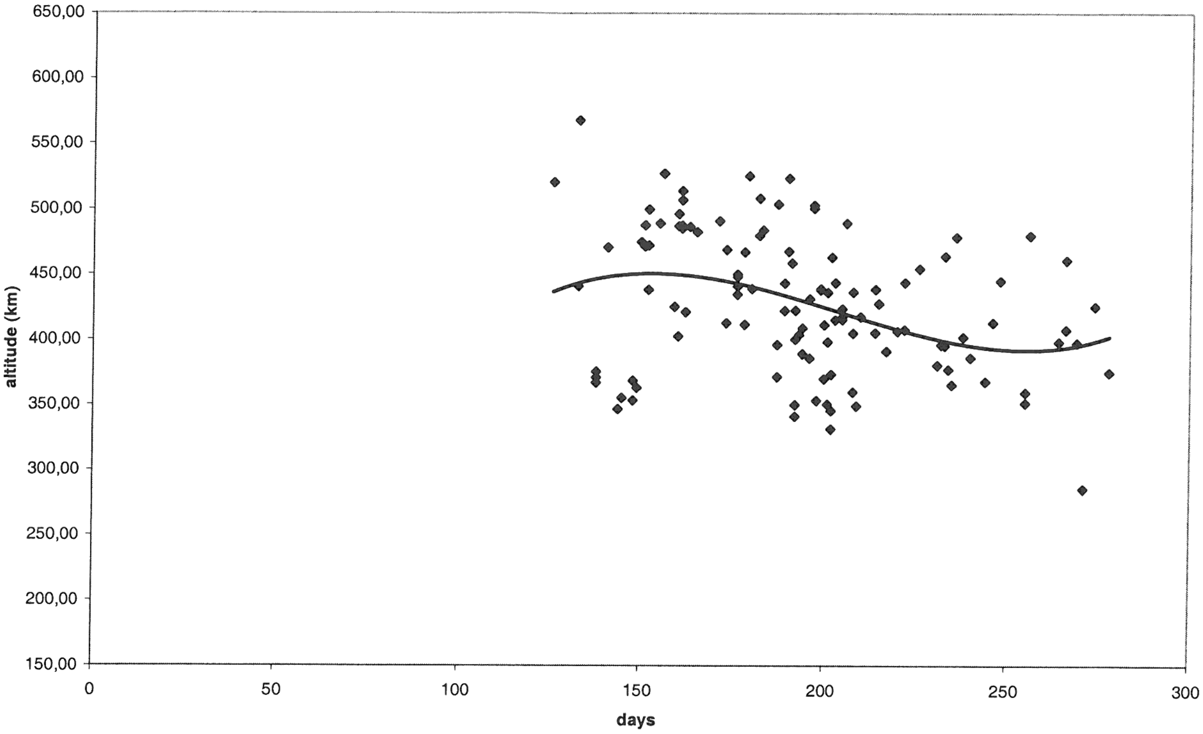
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Fig. 4.

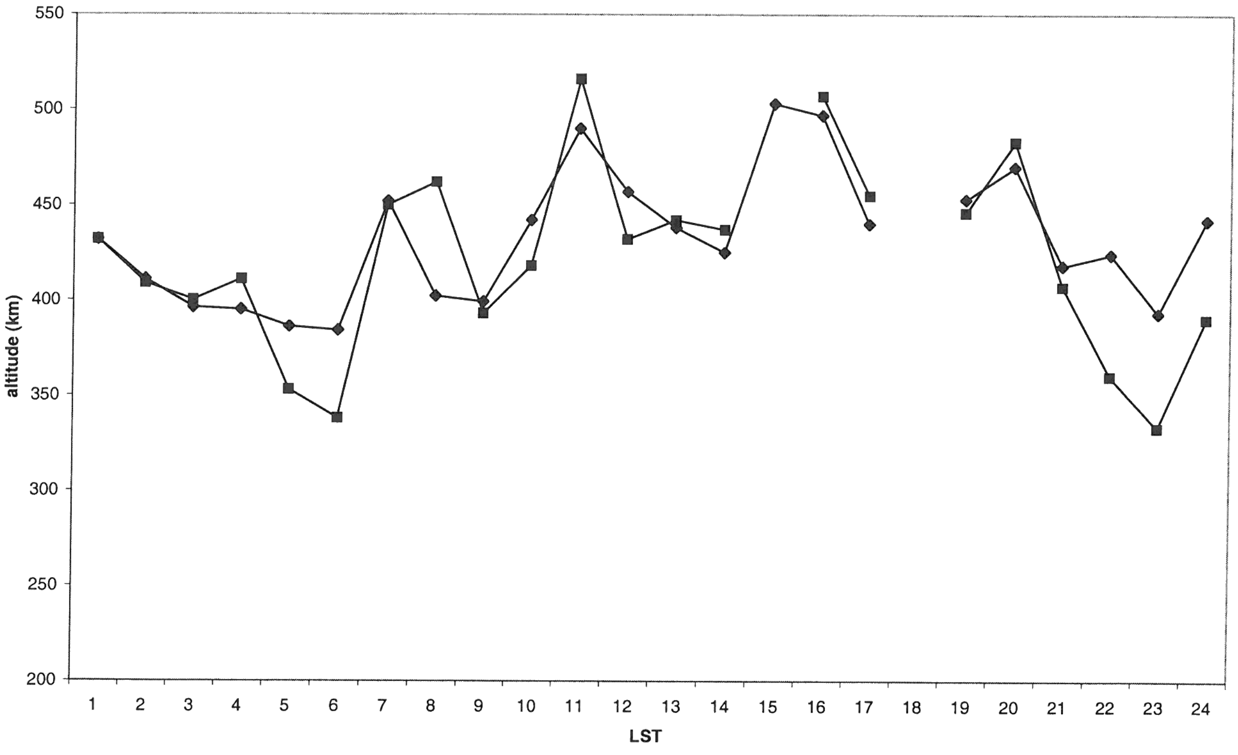
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Fig. 5.