Journal of Physics Special Topics

P1_4 Global Warming: Effects on LEO Satellites

C. Michelbach, L. Holmes, D. Treacher

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

November 5, 2014

Abstract

Satellites in low Earth orbits are subject to drag forces from the Earth's atmosphere, these forces deorbit the satellites over time. The effect of global warming on the rate at which a satellite will deorbit is investigated in this paper. It is found that, while a simplified model would predict a faster deorbit, this is not the case due to interactions at the molecular level.

Introduction

Satellites in low Earth orbit (hereby referred to as LEO), are subject to many factors which help to slowly deorbit said satellite. One of these is the atmospheric drag encountered by the satellite. The drag equation is as follows,

$$F_D = \frac{1}{2}\rho v^2 C_D A \qquad \text{Equation [1]}$$

and the work done by this force is clearly the drag force multiplied by the distance travelled (s). While the atmosphere in LEO is very limited, at the orbital speeds of the satellite and over a long distance, it is certainly sufficient to reduce the velocity of the satellite such that it is eventually deorbited. This paper aims to present a simplified view of global warming and investigate the effects of this simplified model on a satellite in LEO. The simple model in question assumes that the thermosphere is not subject to a temperature increase; only lower levels of Earth's atmosphere are. Secondly, there is an increase in CO_2 in all levels of the atmosphere, this includes the thermosphere.

Theory

It can be assumed, for the purposes of this paper, that the Earth's lower atmosphere behaves as an ideal gas such that,

$$P = \frac{\rho k_B T}{\langle m \rangle} \qquad \text{Equation [2]}$$

where $\langle m \rangle$ is the mean mass of an air molecule and the other symbols hold their usual meanings. Now, at some point in mid-air, the pressure change with respect to the change in altitude (z) can be found in terms of the weight of the air. This gives the relationship,

$$\frac{dP}{dz} = -\rho g \qquad \text{Equation [3]}$$

By differentiating equation 2 with respect to density, we can substitute for the change in pressure in equation 3, giving the following:

$$\frac{d\rho}{dz} = -\rho \frac{\langle m \rangle g}{k_b T} \qquad \text{Equation [4]}$$

By integrating equation 4 between the limits of air density at sea level and at the altitude being investigated, we arrive at the barometric formula for density:

$$\rho = \rho_0 e^{-\langle m \rangle gz/k_bT} \qquad \text{Equation [5]}$$

Discussion

Using the interpretation of global warming stated above, it can immediately be seen that as the temperature of the lower atmosphere increases, the density will decrease. This means that more mass would be contained at higher altitudes as the volume of gas expands and therefore the density at higher altitudes will actually be greater than it was before. Counter to this, the mean mass of an air molecule will also increase as the molar mass of CO_2 (44.01 g mol^{-1}) is greater than the average molar mass of dry air (28.97 g mol^{-1}) [1], which would imply that the density would increase. However, the change in the average mass per molecule is incredibly small in comparison to the change in temperature; the change can be neglected as a result.

From the density increase at LEO, it is intuitive that the work done by the drag force is greater and thus, the satellite will deorbit sooner. But in reality, this is not the case. In fact, the counter is true: global warming is causing satellites in LEO to encounter less air molecules and deorbit much slower [2]. This is due to the cooling effect CO_2 provides at lower densities (such as those in the thermosphere), causing the atmosphere to contract, creating a lower density at LEO [3]. Such cooling arises from collisions between oxygen and carbon dioxide molecules, which transfer energy to the CO_2. This energy is then emitted, but due to the very low density, the majority is emitted into space, which in turn cools the thermosphere [4]. A greater than predicted amount of CO_2 in the thermosphere, due to large amounts of mixing in the Earth's atmosphere [4], increases this cooling and contracting effect even further.

Now, as can be seen in equation [5], a lower temperature will cause the density to increase and therefore contract (assuming the thermosphere can be treated as an ideal gas), meaning that at LEO the density will decreases as air mass is increased at lower altitudes, and therefore the work done by the drag force is also reduced.

Conclusion

To conclude, while in the simple model produced by the authors, a faster deorbit of satellites in LEO is predicted, this is actually counter to the situation presented in reality due to a larger amount of carbon dioxide in the thermosphere than predicted (due to atmospheric mixing) and the cooling effect that this causes.

References

[1] - http://www.engineeringtoolbox.com/molecular-mass-air-d_679.html, accessed on 28/10/14

[2] - http://www.space.com/18430-global-warming-carbon-dioxide-space-junk.html?cid=dlvr.it, accessed on 25/10/14

[3] – "*How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?*", Roble, R. G. and R. E. Dickinson, Geophysical Research Letters 16, 1989

[4] – "*Atmospheric science: Rise in upper-atmospheric carbon*", Stefan Noël, Nature Geoscience 5, 2012