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SPECIAL RELATIVITY EFFECTS FOR SPACE-BASED COHERENT LIDAR EXPERIMENTS

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INTRODUCTION

There is a great need to develop a system that can measure accurately atmospheric wind profiles because an accurate data of wind profiles in the atmosphere constitutes single most input for reliable simulations of global climate numerical methods. Also such data helps us understand atmospheric circulation and climate dynamics better. Because of this need for accurate wind measurements, a space-based Laser Atmospheric Winds Sounder (LAWS) is being designed at MSFC[1] to measure wind profiles in the lower atmosphere of the earth with an accuracy of 1 meter/sec at lower altitudes to 5 meters/sec at higher altitudes. This system uses an orbiting spacecraft with a pulsed laser source and measures the Doppler shift between the transmitted and received frequencies to estimate the atmospheric wind velocities. If a significant return from the ground (sea) is possible, the spacecraft speed and height are estimated from it and these results and the Doppler shift are then used to estimate the wind velocities in the atmosphere. It is expected that at the proposed wavelengths, there will be enough backscatter from the aerosols[2] but there may not be significant return from the ground. So a coherent (heterodyne) detection system is being proposed for signal processing because it can provide high signal to noise ratio and sensitivity and thus can make best use of low ground returns. However for a heterodyne detection scheme to provide best results, it is important that the receiving aperture must be aligned properly and for the proposed wind sounder, this amounts to only a few microradians tolerance in alignment. It is suspected that the satellite motion relative to the ground may introduce errors in the order of a few microradians because of special relativity. Hence the problem of laser scattering off a moving fixed target when the source and receiver are moving, which was not treated in the past in the literature, was analyzed in the following, using relativistic electrodynamics[3] and applied to the case of the space-based coherent lidar, assuming flat ground. We are interested in developing analytical expressions for the location of the receiving point for the return with respect to the satellite, receiving angle and Doppler shift in frequency and amount of tip, all as measured in the satellite moving coordinate system and the diffuse scattering angle at the ground which does not require any compensation. All the three cases of retro-reflection, specular reflection and diffuse scattering by the ground should be treated though retro-reflection and diffuse scattering are more important.

METHOD OF ANALYSIS AND PATH GEOMETRY

Figure 1. shows a Laser Atmospheric Wind Sounder System, called AEOLUS. Initially we assume earth is assumed to be flat and a satellite is moving with a horizontal velocity V (along the x axis, parallel to the ground) at a height H above the ground. Our goal is to find out the path of a light ray from a moving source (satellite) to the stationary ground, as observed from the ground (whose coordinate system is not moving) and the paths taken by the reflected and backscattered rays from the ground towards the satellite as observed by a receiver adjacent to the transmitter in the moving coordinate system.

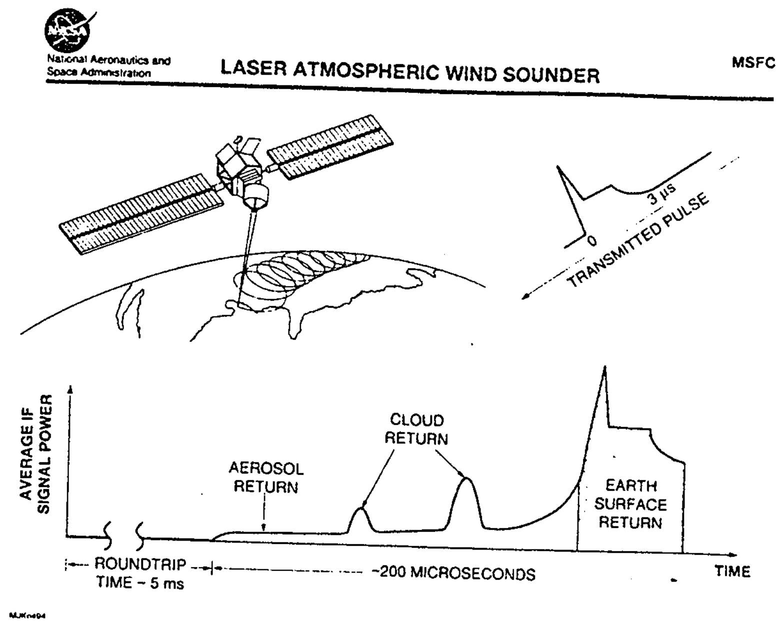

Fig.1. AEOLUS-Laser Atmospheric Wind Sounder

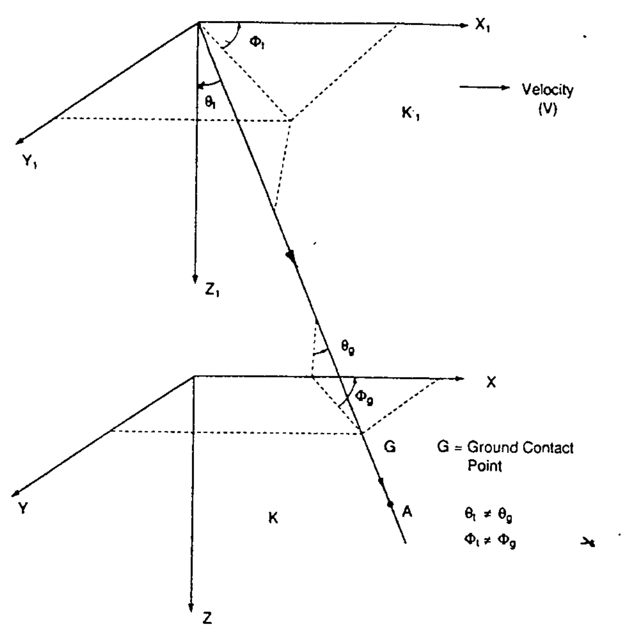

Fig.2. Coordinates Systems for the Analysis

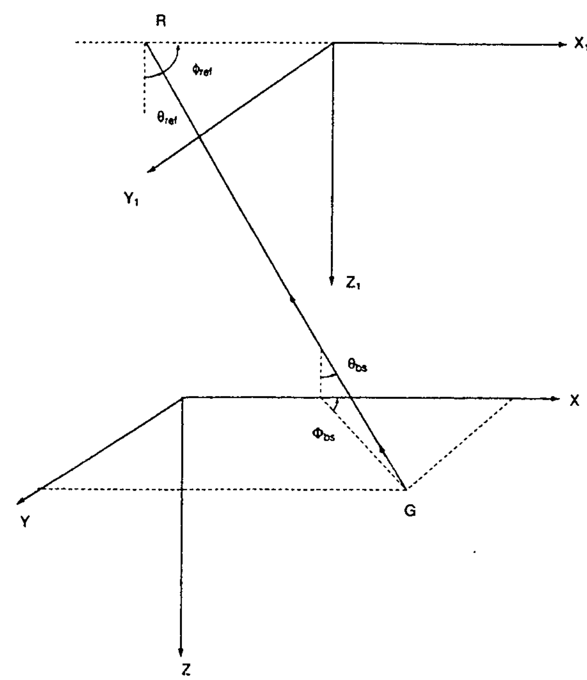

Fig.3. Retro-reflection Path Geometry

Figure 2. shows two coordinate systems. K system is a fixed coordinate system (coordinates are x, y, z and t). K_1 system describes the satellite motion and is moving with respect to K at a velocity V along the x axis (coordinates in K_1 are x_1 , y_1 , z_1 and t_1). A laser transmitter is located at the origin of the K_1 system. Assume at $t = t_1 = 0$, the point ($x_1=0$, $y_1=0$, $z_1=H$) of K_1 coordinate system will go past the point (x=0, y=0, z=0) of coordinate system K to set up proper Lorentz transformations.

We used ray formulation first. For this consider a light signal transmitted from the origin of the K_1 system with spherical coordinate angles θ_t and ϕ_t towards the fixed system on the ground (Figure 2). Assume that light is pulse of very short duration so that during the transmission, the displacement of the origin of the coordinate system can be ignored. For the transmitted ray, the coordinates in the moving frame and fixed frame are calculated. After the ray is incident on the ground, the returning ray angles are determined, depending whether the return is due to retro-reflection, specular reflection and diffuse reflection. The returning ray coordinates are then determined again in both coordinate frames. Since the motion is parallel to x-axis, z coordinate separation (H) remains constant and this is used to calculate the time of transmission from source to the ground and from ground to receiver. Since ray formulation can not give Doppler shift and changes in the electromagnetic fields and reflectance, we used a wave formulation, which provided with the above results as well as verification for some of the results, achieved through the ray formulation. All the details are being published in a NASA Technical Memorandum[4].

GENERAL RESULTS

When a retro-reflector is located at the point where the above ray is incident on the ground, The incident is scattered back along the receiving angle in the fixed coordinate system (Figure 3). In this case, at the point of return in terms of the satellite coordinate system:

Coordinates of the point of return:

$$x_{1ret} = -2\,H\,\alpha\,\frac{1+\alpha\,\sin(\theta_t)\cos(\phi_t)}{(1-\alpha^2)\cos(\theta_t)} \qquad y_{1ret} = 0 \qquad z_{1ret} = z+H = 0 \tag{1}$$

The spherical coordinate angles and the received frequency ω_{rec}:

$$\cos(\theta_{rec}) = \frac{(1-\alpha^2)\cos(\theta_t)}{1+\alpha^2+2\alpha\sin(\theta_t)\cos(\phi_t)} \qquad \tan(\phi_{rec}) = \frac{(1-\alpha^2)\sin(\theta_t)\sin(\phi_t)}{2\alpha+(1+\alpha^2)\sin(\theta_t)\cos(\phi_t)} \tag{2}$$

$$\omega_{rec} = \omega_t \frac{1+\alpha^2+2\,\alpha\,\sin\theta_t\,\cos\phi_t}{1-\alpha^2} \tag{3}$$

For specular reflection, we assume that the light is reflected back according to Snell law in the fixed system (K). A further analysis gives us:

Coordinates for the point of return:

$$x_{1ret} = 2\, H \tan(\theta_t) \cos(\phi_t) \qquad y_{1ret} = 2\, H \tan(\theta_t) \sin(\phi_t) \qquad z_{1ret} = 0 \tag{4}$$

For the receiving angles and frequency:

$$\cos(\theta_{rec}) = \; = -\cos(\theta_t) \qquad \tan(\phi_{rec}) = \tan(\phi_t) \qquad \omega_{rec} = \omega_t \tag{5}$$

However $\theta_{rec} = -\theta_t$ and $\phi_{rec} = -\phi_t$. Also note that there is no Doppler shift.

For the case of diffuse scattering, the rays of interest lean towards backscattering direction, as opposed to forward reflection. For an arbitrary direction, results are given in the memorandum[4]. It can be shown that most of the rays will miss the receiver except a few near the backscattering direction and in particular, it is possible to find a direction (θ_b and ϕ_b) at the ground for which no compensation is needed and these angles are given as:

$$\cos(\theta_b) = \frac{\cos(\theta_t)\sqrt{1-\alpha^2}}{1-\alpha \sin(\theta_t)\cos(\phi_t)} \qquad \tan(\phi_b) = \frac{\sin(\theta_t)\sin(\phi_t)\sqrt{1-\alpha^2}}{\sin(\theta_t)\cos(\phi_t) - \alpha} \tag{6}$$

For this case with no need for adjustments at the receiver, as expected, the coordinates of the point of return are:

$$x_{1ret} = 0 \qquad y_{1ret} = 0 \qquad z_{1ret} = 0 \tag{7}$$

For the received frequency:

$$\omega_{rec} = \omega_t \frac{1 + \alpha \sin\theta_t \cos\phi_t}{1 + \alpha \sin\theta_t \cos\phi_t} \tag{8}$$

RESULTS AND SUMMARY FOR THE PROPOSED WIND SOUNDER

AEOLUS has a proposed altitude of 350 Kilometers, a velocity of 7704.3 meters/sec, nadir angle of 30^0, azimuth angle of 45^0 and wavelength of 2 μm. For this data, in the case of retro-reflection, the returned beam will miss the satellite by about 20.7 meters. If the beam foot print is large on the ground, still a part of the return may be received. Received Angles are 30.0018 degrees for nadir and 44.9958 degrees for azimuth. These correspond to a tilt of 31.43 μ radians for nadir and 73.33 μ radians for azimuth. For higher velocities (v/c >= 0.1), the receiver may miss the backscatter completely. Angles, through which the receiver has to be tipped, will be much higher. For LAWS, backscatter may be reasonably acceptable. In case of specular reflection off the ground, if the transmission angle is zero, no corrections are required. In this case, for non-zero transmission angles, reflected signal will not see the receiver. In case of diffuse scattering off the ground, for any transmission angle, there exists a return direction, for which no compensation is required at the receiver. For AEOLUS data, this direction differs from the incidence angles at the ground by about 15.7 microradians for elevation angle (theta) and by 36.63 microradians for azimuth (phi) and hence provides a good backscatter and so the system should be successful. Analytical results for the Doppler shift in the frequency show that in case of specular reflection, there is no Doppler shift due to the satellite motion and the relativity. In case of backscattering and diffuse scattering, there are Doppler shifts due to the satellite motion and relativity. It is found that the Doppler shift due to the relativity is in the order .025 % to .1% for a wind of 1 meters/sec and it should be corrected for.

RECOMMENDATIONS

First, the analysis has to be redone, taking into consideration horizontal movement of the satellite and vertical movement of the target with flat earth. Then relax the assumption that the earth is flat to arrive the more accurate design criteria. Emphasis should be on backscattering and diffuse targets. The light incident on the ground has a finite area. For flat earth, correction for the fact that the light at the receiver is contributed by all the points from the ground, may not be serious. But when we use spherical coordinates, we must take this into account as the local normal is different from point to point. Compare the signal contribution due to relativistic effects with that from satellite motion and wind for a more general analysis that involves spherical earth. Error estimates in wind have to be calculated for the more general case. No Results have appeared in the literature how the Fourier spectrum of a pulse changes for the return geometry under consideration. Develop an analysis for this problem and compare the relativistic contribution.

SUMMARY

In summary, we derived several analytical results based on the special theory of relativity, useful for space-based lidar experiments. We applied our results to the proposed AEOLUS system and found that the current design recommendations are within acceptable tolerances. Some important next steps that will improve the analysis and provide better design rules have been identified.

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