

## High-resolution stratospheric dynamics measurements with the NASA/JPL Goldstone Solar System Radar

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**Abstract.** We have used, for the first time that we are aware of, the NASA/JPL Goldstone planetary radar to study the Earth's atmosphere. With its high bandwidth and power, we were able to achieve a height resolution of 20 m, which is significantly better than the usual 150-m resolution for stratospheric radars. Here we discuss the observation of a very thin scattering layer that persisted over several hours at the same height just above the tropopause. We question the assumption of turbulent radar scatter based on the available evidence, and also investigate the two-minute oscillation observed in the vertical velocity.

### Introduction

One of the outstanding scientific problems in middle atmosphere dynamics is the role that stratospheric turbulence plays in the vertical transport of minor constituents such as ozone, water vapor, aerosols, and pollutants from volcanic eruptions and supersonic jet planes. Because the turbulence occurs in extremely thin layers (due to the high convective stability of the stratosphere), it has been difficult to observe its detailed structure. A stratosphere-troposphere (ST) radar typically has a range resolution of 150 m, but stratospheric turbulence often has finer-scale features of the order of tens of meters.

To overcome the range-resolution problem the Arecibo bistatic S-band planetary radar with its capacity for very fast phase modulation was used to study the stratosphere [Woodman, 1980; Jerkic *et al.*, 1990]. However, that system is currently not in operation.

We have applied the same technique and used, for the first time that we are aware of, the NASA/Jet Propulsion Laboratory Goldstone planetary radar to study the Earth's atmosphere. Here we present the first results from this experiment and discuss aspects of the observed dynamics and their implications for the radar scattering mechanism.

### Experimental Set-Up

Two antennas of the Goldstone Solar System Radar were used in a bistatic configuration. Both the transmitting (DSS-14) and receiving (DSS-12) antennas are fully steerable parabolic dishes with diameters of 70 m and 26 m. The latter was located 21.6 km, roughly southeast, from the former. The S-band carrier frequency (2320-MHz, 12.9-cm wavelength) was used in continuous-wave (CW) mode with a 1023-length, 0.125- $\mu$ s-baud pseudorandom binary phase code [MacWilliams and Sloane, 1976]; this type of coding is similar to the frequency-modulated CW (FMCW) technique used in boundary-layer radars [Richter, 1969]. Up to 400 kW of average transmitted power was used. The resultant altitude resolution of 20 m is the best that we know of among ST radars and is only rivaled in the stratosphere by what was achieved using the old Arecibo system. For this experiment we took 99 coherent integrations, 128 FFT points, and 9 spectral averages for a time resolution of 15 s and Doppler velocity resolution of 5 cm s<sup>-1</sup> (a time resolution as short as 4 s has been used successfully in previous experiments; we lengthened the integration time simply to avoid filling up the recording disk too quickly). For further information on the Goldstone system we refer the reader to Dvorsky *et al.* [1992].

A serious drawback of this bistatic geometry is the shallowness of the intersection volume at stratospheric heights. The narrowness of the antenna beams (a near-field pencil beam for DSS-14 and a diverging beam for DSS-12) and the 21.6-km baseline combined to yield a common volume with a depth of only about 300 m at 18 km altitude. Thus the antennas had to be scanned up and down to cover a wider range of heights. A receiving antenna adjacent to the transmitting antenna was available, which would have provided a much improved simultaneous altitude coverage, but the direct spillover of power was deemed so great that it would overwhelm any backscattered signal from the atmosphere.

### Data

The experiment on which we report was conducted on 25 August 1995, beginning at 0600 UT and lasting until 1300 UT. During the first 100 minutes of the

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experiment we moved the common bistatic volume between about 17 and 18 km in altitude and discovered thin scattering layers at several heights. After this we fixed the antennas at one elevation angle and were able to observe one particular layer for the remainder of the time (Figure 1). The top panel is a color-scale map of the backscattered signal-to-noise ratio (SNR); each time slice has been self-normalized to bring out the peaks in the signal. At the beginning of the plot there is a layer at 17.7 km that soon descends as another layer comes down into the frame; this latter layer remarkably remained within the same 300-m height window for the rest of the experiment (about 4.5 hours). Note that the layer appears to split in two at around 250 minutes and 300–330 minutes. Because the plot is self-normalized, changes in the absolute SNR with time can be discerned by the variation in the level of signal outside the scattering layer—higher power outside corresponds to lower peak signals. Also because the intersection of the two antenna beams does not yield a uniform gain over the entire volume, the lower SNR away from the center of the common volume may be due to loss of gain; for example, the lower absolute SNR around 300 minutes is likely due to this effect because the scattering layer at that time is near the bottom of the common volume.

The vertical velocity as measured by the first moment of the Doppler velocity spectrum was very uniform with height across the scattering layer. Thus, we display the height-integrated vertical velocity in the bottom panel of Figure 1. In regions where the velocity oscillated with significant amplitude, the scattering layer undulated up and down in sync, suggesting that the layer was advected by the vertical winds. Of special interest is the rapid oscillation around 220 minutes that has a period of about 2 minutes, which can also be observed in the frequency-domain power spectrum of the velocity fluctuations (Figure 2). The large, isolated peak that is at a higher frequency than the Brunt-Väisälä cutoff corresponds to a period of 2 minutes.

We also have rawinsonde data from Desert Rock, Nevada, which provided us with temperature and horizontal wind profiles at 0000 and 1200 UT on the same day. Desert Rock is about 150 km northeast of Goldstone and was the nearest, regularly launching site for weather balloons. The rawinsonde data had a vertical resolution of the order of 100 m (the sampling was uneven) in the height region of interest. To calculate the Brunt-Väisälä frequencies and the Richardson numbers, the data points were interpolated and evenly resampled at 100-m intervals. Figure 3 is the Richardson number profile calculated from the rawinsonde temperature and winds at 1200 UT.

## Interpretation

Let us first try to understand the 2-minute oscillation in the vertical velocity. Anticipating the presence of gravity waves, one does not normally expect a periodicity shorter than the Brunt-Väisälä cutoff, so it seems

rather surprising. However, there are several possible explanations.

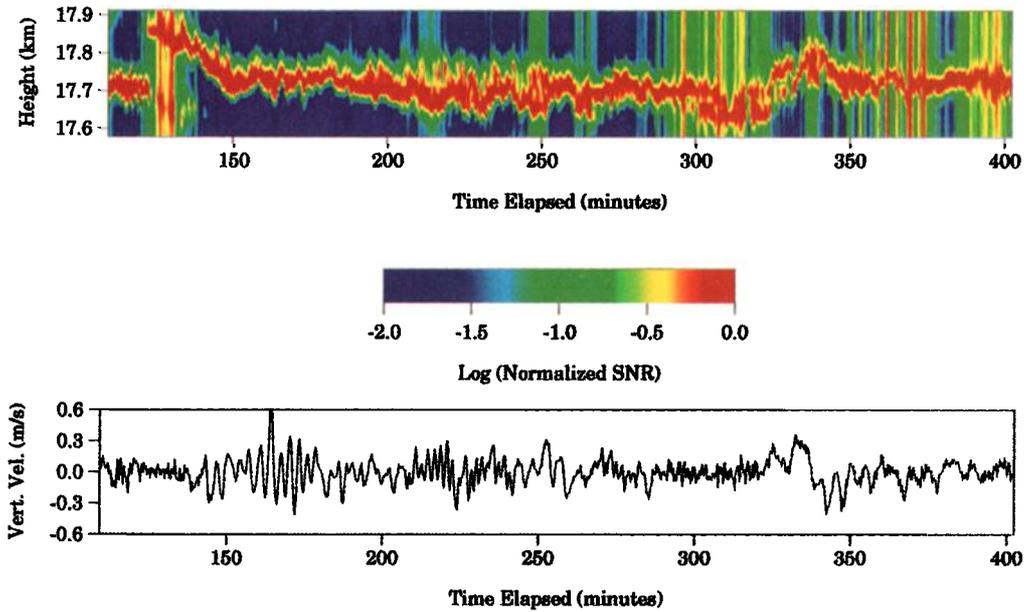
First, the observed oscillation period could have been Doppler-shifted by the background motion of the medium, i.e., the Lagrangian wave period may have been longer than the Brunt-Väisälä period but was observed as being shorter from the Eulerian perspective. Unfortunately, without knowing the wave vector we cannot estimate how much Doppler shift the measured background wind could have introduced. If we assume that the wave was propagating parallel to the horizontal wind, thereby receiving the maximum leverage for Doppler shifting, then an intrinsic period of 4 minutes, together with the mean observed wind speed of  $6 \text{ m s}^{-1}$ , would require a horizontal wavelength of  $\leq 1.5 \text{ km}$ . That is an extremely short horizontal wavelength for a gravity wave.

Second, the wave could have been acoustic. From the rawinsonde temperature profile we calculated the acoustic cutoff period to be above 2 minutes, so sound waves could have propagated. Also an electric storm was observed locally during the experimental period; convective storms have been known to generate infrasound waves close to the Brunt-Väisälä period [Georges, 1973]. The atmosphere also appears to have resonant modes close to the acoustic cutoff [Jones and Georges, 1976] that have been observed to be excited by volcanic eruptions [Widmer and Zürn, 1992]. To estimate the source power necessary to generate the observed vertical velocity amplitude of  $w \sim 0.3 \text{ m s}^{-1}$ , we calculate the average power flux density  $F = 0.5\rho c w^2$ , where  $\rho = 0.14 \text{ kg m}^{-3}$  is the ambient air density and  $c = 290 \text{ m s}^{-1}$  is local sound speed (calculated from the rawinsonde data). We estimate the emitted source power (neglecting absorption effects) by integrating  $F$  over a hemisphere of radius  $r$ :  $P = 2\pi r^2 F$ . If we assume that the source was directly below the observation volume at ground level, i.e.,  $r = 18 \text{ km}$ , then we get  $P = 4 \text{ GW}$ . This is two orders of magnitude larger than the estimate of average storm-generated acoustic radiated power of 20 MW [Georges, 1973].

Third, the observed vertical velocity oscillation could have been a manifestation of Kelvin-Helmholtz rolls being advected across the common volume by the background horizontal winds. If so, we would expect the thickness of the instability layer,  $\Delta z$ , to be related to the horizontal periodicity,  $\lambda$ , by  $\Delta z = \lambda/\pi$ , where  $\lambda = UT$ , the horizontal advection velocity,  $6 \text{ m s}^{-1}$ , times the oscillation period, 2 minutes. The result is  $\Delta z = 200 \text{ m}$ , which is several times thicker than the observed scattering layer. Furthermore, we note in Figure 3 that the Richardson number does not take a dip at the height of the layer.

Next, we estimate the turbulence energy dissipation rate,  $\epsilon$ , in the layer assuming that the radar scattering resulted from turbulence. From Hocking [1985] we have  $\epsilon = 0.4\omega_B(\Delta v)^2$ , where  $\omega_B = 0.026 \text{ rad s}^{-1}$  is the local Brunt-Väisälä frequency calculated from raw-

Goldstone S-Band DSS-14/12 August 25, 1995

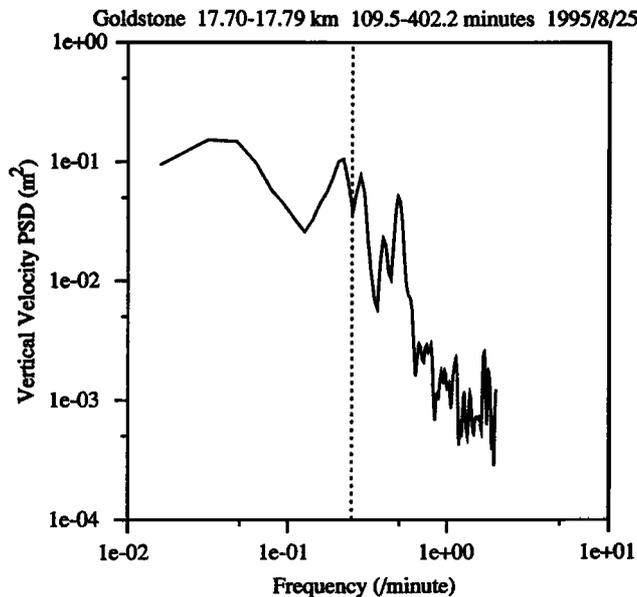


**Figure 1.** The top panel is a color-scale map of radar backscattered signal-to-noise ratio versus height and time. Each time slice is self-normalized for maximum contrast. The center of the bistatic common volume is at 17.8 km. The bottom panel is the height-integrated vertical velocity versus time. The time elapsed is referenced to the start of the experiment at 0600 UT.

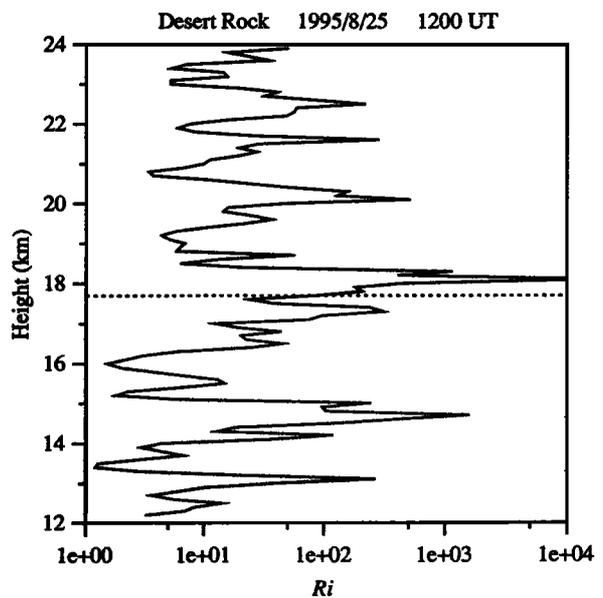
insonde temperatures and  $\Delta v = 0.1 \text{ m s}^{-1}$  is a typical half-width of the observed Doppler velocity spectra. The result is  $\epsilon = 0.1 \text{ mW kg}^{-1}$ .

Can such a weakly turbulent layer produce strong radar echoes at S-band? Taking the radar cutoff wavelength to be  $\lambda_c = 8\pi\eta$  [VanZandt, 1992], where  $\eta = \nu^{3/4}\epsilon^{-1/4}$  is the Kolmogorov microscale and  $\nu = 9.3 \times$

$10^{-5} \text{ m}^2 \text{ s}^{-1}$  is the kinematic viscosity of the air calculated from rawinsonde data, we arrive at  $\lambda_c = 24 \text{ cm}$ , which is longer than the 12.9-cm wavelength of the radar. It appears that turbulent scatter should only be marginally effective at this radar wavelength. This suspicion is further bolstered by the lack of correlation between Doppler spectral width and echo power (not plotted here due to limited space), and the high values of the Richardson number at the scattering layer height.



**Figure 2.** Power spectral density of the vertical velocity fluctuations. The vertical dotted line indicates the local Brunt-Väisälä frequency (corresponding to a period of 4 minutes) calculated from the rawinsonde temperature data.



**Figure 3.** Richardson number profile calculated from the rawinsonde temperature and winds. The horizontal dotted line indicates the approximate height of the radar scattering layer.

## Summary Discussion

What is the physical nature of this very thin and persistent radar scattering layer that we observed in this experiment? Conventional wisdom suggests shear-instability-induced turbulence in a highly stratified environment. The evidence here, however, does not support such preconceived notions very well: (1) The Doppler spectral width does not increase with echo power, (2) even assuming turbulence, the calculated cutoff due to viscosity occurs at a longer scale than the radar wavelength, and (3) the Richardson number profile calculated from rawinsonde data is not reduced at the scattering layer height. And what kind of physical mechanism can sustain a turbulence-producing gradient for over several hours at the same height? One might argue against the relevance of the Desert Rock rawinsonde data due to its distance away from the radar, but the persistence of the layer over many hours suggests that it was wide-spread horizontally (assuming advection by the background wind, which was blowing towards the northeast at the layer level, i.e., in the direction of Desert Rock). The lack of rawinsonde resolution is also a problem, especially since we know that temperature sheets of the order of a few meters exist in the stratosphere and can cause specular reflection for VHF radars [Luce *et al.*, 1995]. Could such sheets (possibly created by viscosity waves produced by acoustic waves reflecting from the steep temperature gradient just above the tropopause [Hocking *et al.*, 1991]) also affect S-band scatter? Such speculations can only be investigated with further experiments using collocated, high-resolution temperature and wind measuring instruments.

The two-minute oscillation was also an intriguing feature. However, without additional information we cannot draw any firm conclusions regarding its origin. Simply being able to observe a wider range of heights simultaneously would be of great help, since wavelike (or otherwise) characteristics should be discernible in the vertical variation of the oscillation. With the assistance of JPL engineers we hope to devise a scheme for doing just that in the future. Note also that we only explored a very small altitude region in this experiment. In the future we hope to look further above into the stratosphere and below into the troposphere to study other interesting phenomena.

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