HIGH-RESOLUTION OBSERVATIONS OF STRATOSPHERIC DYNAMICS WITH THE NASA GOLDSTONE SOLAR SYSTEM RADAR

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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), its observation has been difficult. 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; *Ierkic 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.

Two antennas of the Goldstone Solar System Radar were used in a bistatic configuration. Both the transmitting (DSS-14) and receiving (DSS-12) antennas were 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) was used in continuous-wave (CW) mode with a 1023-length, 0.125-μs-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. 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^{-1} (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. 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

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coverage, but the direct spillover of power was deemed too great that it would overwhelm any backscattered signal from the atmosphere.

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 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 gray-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 (difficult to see from this figure but quite clear when the plots are expanded in time scale), 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 could also be observed in the frequency-domain power spectrum of the velocity fluctuations.

We also have rawinsonde data from Desert Rock, Nevada (about 150 km northeast of Goldstone), which provided us with temperature and horizontal wind profiles at 0000 and 1200 UT on the same day. The temperature profiles showed that the radar scattering layer was just above the tropopause, and that the local Brunt-Väisälä period was 4 minutes. Also, the Richardson number profile calculated from the rawinsonde temperature and winds showed no significant reduction in the height region of the scattering layer and was much greater than 1.

What was 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, however, did not support such preconceived notions very well: (1) The Doppler spectral width did not increase with echo power, (2) even assuming turbulence, the calculated cutoff due to viscosity [*VanZandt*, 1992] occurred at a longer scale (24 cm) than the radar wavelength (13 cm), and (3) the Richardson number profile calculated from rawinsonde data was not reduced at the scattering layer height. And what kind of physical mechanism could have sustained 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 resolution (the rawinsonde sampled

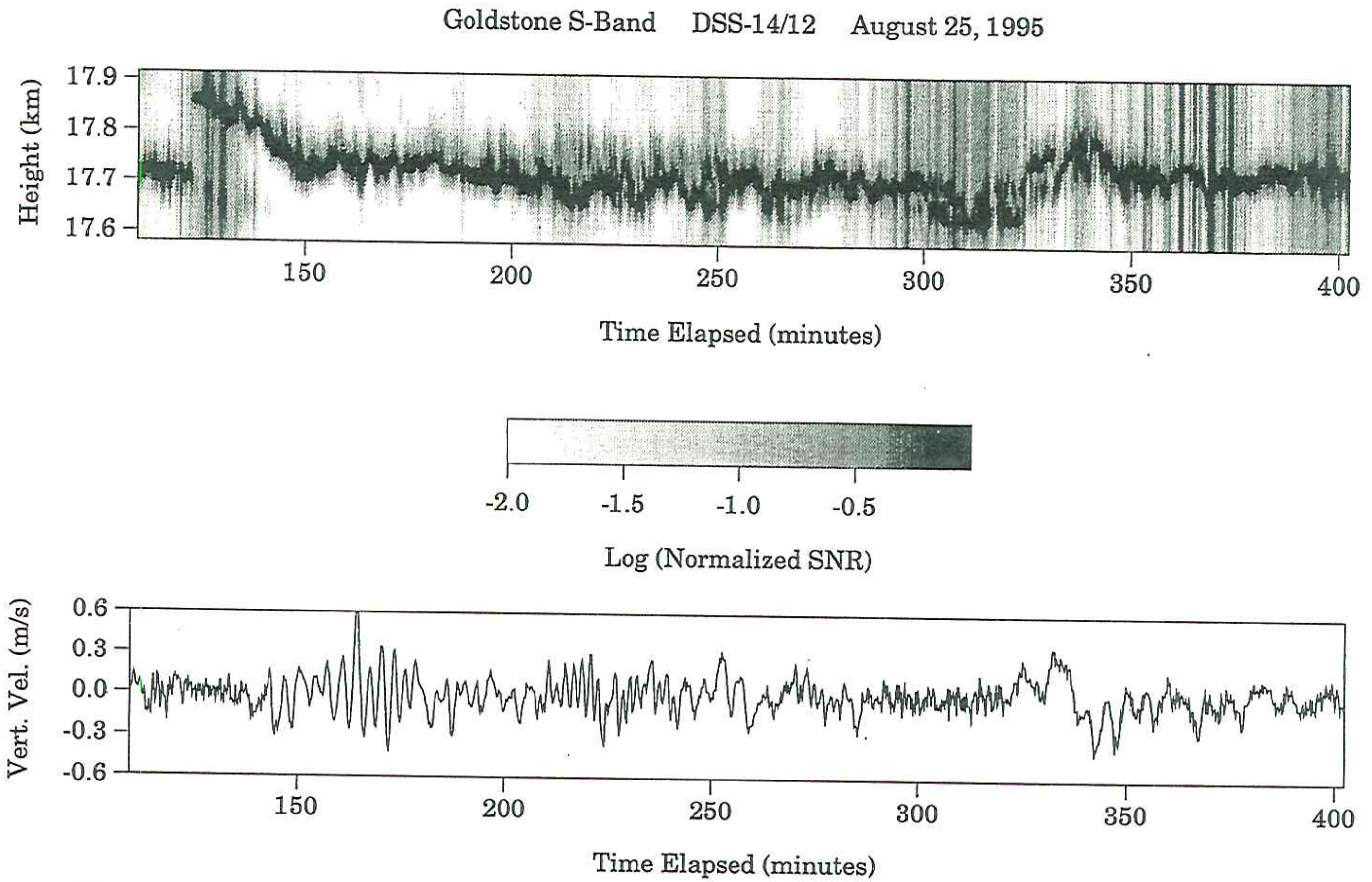

Figure 1: The top panel is a gray-scale map of radar backscattered signal-to-noise ratio versus height and time. Each time slice is self-normalized for maximum contrast. The center of the bistatic common volume is at 17.8 km. The bottom panel is the height-integrated vertical velocity versus time. The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

unevenly on the order of several tens of meters) was 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 such as a Doppler Rayleigh lidar and balloon-borne thermometers.

The two-minute oscillation was also an intriguing feature. However, without additional information we cannot draw any firm conclusions about whether is was a Doppler-shifted gravity wave, an acoustic wave, or Kelvin-Helmholtz rolls. 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. 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.

A more extensive analysis has been submitted to *Geophys. Res. Lett.* [*Cho et al.*, 1996].

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