Section 3.3 Coherent scatter radars

The ionosphere is a remarkable medium for electromagnetic wave propagation, exhibiting a birefringent (double-valued) index of refraction that can be less than unity. Since the beginning of the radio age, it has been known that radio signals reflect from the ionosphere when their frequency is less than the ionospheric critical frequency and refract back to Earth when it is less than the maximum usable frequency (MUF). This is the principle behind radio sounding and ionosondes, the primary means of probing the ionosphere prior to the space age. An important limitation of ionospheric sounding is that it cannot be used to probe altitudes above the $F$ peak. Around the time of the start of the space age, considerable effort and resources were consequently devoted to investigating “incoherent scatter,” weak radio scattering from thermal fluctuations in the ionospheric plasma. Incoherent scatter provides relatively unambiguous information about the state parameters of the ionosphere (number density, temperature, composition, collisionality, the magnetic field, drifts) at all altitudes. However, incoherent scatter radars (ISRs) are powerful, large, expensive facilities requiring considerable resources to field, operate, and maintain. The power-aperture product of incoherent scatter radars is conveniently measured in megawatt-acres. There are just a dozen ISRs operating around the world.

In addition to incoherent scatter, “coherent scatter” can also be detected by radars and used to probe the ionosphere at many altitudes. The meaning of this term is somewhat ambiguous but generally means scattering that is stronger than incoherent scatter but weaker than total reflection. The detection of coherent radar scatter generally implies the existence nonthermal irregularities in the plasma, indicative of free energy, waves, and instabilities. The resulting echoes can be very strong, meaning that coherent scatter radars can work at modest power levels and with relatively compact antennas. Autonomous, long-term coherent scatter radar observations are practical, economical, and commonplace. Coherent scatter can be used to monitor and study a number of different phenomena, particularly but not only during disturbed conditions.

Coherent scatter can occur in the mesosphere, where the scattering cross section of neutral density fluctuations driven by neutral turbulence is enhanced by ambient $D$-region electrons. In the polar summer mesosphere, the scattering cross-section is further enhanced by reduced diffusion rates related to charged ice crystals, the root cause of polar mesospheric summer echoes (PMSE). In the ionospheric $E$ region, Farley-Buneman and gradient drift plasma instabilities produce intense field-aligned plasma irregularities (FAIs) which are easily detected by coherent scatter radars situated and configured so as to meet the conditions for field-aligned backscatter. The FAIs are particularly strong in the equatorial and auroral electrojets but also occur at middle latitudes in conjunction with irregular sporadic $E$ ($E_s$) layers. FAIs also occur in meteor trails throughout the MLT region. Near the dip equator, coherent scatter arises from altitudes near 150 km during the day for reasons that are not understood.

In the $F$ region, Rayleigh Taylor-type and/or $\mathbf{E} \times \mathbf{B}$ instabilities also generate strong FAIs. At high latitudes, the resulting coherent scatter is utilized to monitor the convection pattern. At low latitudes, the FAIs are responsible with so-called “equatorial spread $F$.” This is a common phenomenon that is very disruptive to radio communication and navigation systems and is consequently a focus of space weather research. At middle latitudes, FAIs can accompany medium-scale traveling ionospheric disturbances (MSTIDs) and are associated with midlatitude spread $F$. MSTIDs and irregular $E_s$ layers appear to be related, but the connection is not well understood. Finally, FAIs can be produced through ionospheric modification (heating) in the $E$ and $F$ regions and detected using coherent scatter.

The methodology for using coherent scatter data vary widely. Sometimes, the backscattered power intensity is informative in itself, particularly when it is sorted into range and time bins (range-
time-intensity format). Data such as those in Fig. 1 were sufficient to demonstrate that equatorial spread $F$ was caused by a Rayleigh Taylor-type plasma instability that drives regions of depleted plasma through the $F$ peak into the topside in its nonlinear stage of evolution. Note that calibrating the backscattered power in an absolute sense is very difficult and that the signal-to-noise ratio (SNR) is the most common data product.

The range resolution of a pulsed radar is limited mainly by the system bandwidth but is as fine as about 150 m for many systems in use today. The time resolution is determined by the intensity of the backscatter and the desired level of statistical confidence. In the high SNR limit, in which many coherent scatter radars work, depending on the radar pulse rate and the manner in which spectral processing is performed, a high degree of statistical confidence can often be obtained with integration times of the order of few seconds.

![Figure 1: Coherent scatter observations of equatorial spread $F$ event over Jicamarca plotted in range-time-intensity format.](image)

Sometimes, even the absence of ionospheric backscatter can be informative. For example, SuperDARN HF radars often receive strong ground clutter — backscatter from the ground detected along refracted ray paths. Variations in the backscatter intensity versus group delay are indicative of changes in the ionosphere through which the signals propagate. Periodic variations indicative of gravity waves and traveling ionospheric disturbances are often evident in the data. The characteristics of the waves can be deduced by comparing signals received through different radar beams.

Additional information is contained in the Doppler spectrum of the echoes. The Doppler spectrum can be measured with almost limitless precision by CW radars from which long, unbroken time series data are available. For pulsed radars, we must distinguish between underspread and overspread targets. With the former range and frequency aliasing can be avoided with the use of simple pulse-to-pulse sampling schemes. This is untrue for the latter, necessitating the use of more complicated pulsing and/or data analysis methodologies, often resulting in greater ambiguity. The precision of Doppler shift measurements depends on the length of the time series analyzed as well as on the radar wavelength. Precision of the order of a few m/s is typical in many applications.

Finally, spatial information about the scattering medium in the direction normal to the radar
beam can be obtained through electronic beam steering or through spaced antenna methods and radar interferometry. The former method is used by SuperDARN-class radars, and the latter by partial-reflection drift (PRD) and meteor radars. Both are used by large facilities like Jicamarca and the MU radar in Japan. With radar interferometry, the bearing to a target can be determined from differences of the phases of signals received on antennas separated in space. The angular width of the targets can be determined from the coherence, the modulus of the cross-correlation of signals from spaced antennas. In the event that multiple antenna pairs are available for reception, the angular distribution of the target can be determined continuously. Combining this information with information from range gating, volumetric images of the radar target can be made. The spatial resolution of the images in the direction normal to the beam is not diffraction limited. In the high SNR case, the resolution of the images can be considerably finer than the diffraction limit. Fully exploiting the capabilities of radar imaging is a frontier research area in radio science.

Coherent scatter clearly provides contextual information for studying a number of important aeronomic phenomena. Its main shortcoming, however, is that it is not always directly or obviously related to ionospheric state parameters. Notable counterexamples exist. The Faraday rotation of radar signals returned to Earth by coherent scatter can be used to determine electron density profiles unambiguously. Meteor trails drift with the background neutral wind which can consequently be inferred from the Doppler shift of the coherent scatter echoes. The Doppler shifts of coherent echoes from $F$-region irregularities at high latitudes are are useful proxies of the line-of-sight $\mathbf{E} \times \mathbf{B}$
convection speed, although refraction and other issues make the correspondence imperfect. The Doppler shifts of coherent scatter from Farley-Buneman turbulence is closely related to the ion acoustic speed which is itself related to electron and ion temperatures.

A few studies have been performed to associate fundamentally the characteristics of coherent scatter with atmospheric or ionospheric turbulence parameters. For observations of mesospheric turbulence, the Doppler spectrum of the coherent scatter can be rigorously related to the turbulent energy dissipation rate. For coherent scatter from the $F$ region, attempts have been made to associate the shape of the Doppler spectrum with the underlying turbulence wavenumber spectrum in the context of so-called “collective wave scattering theory,” although the results of these analyses remain to be validated. In the main, the methods for analyzing and interpreting coherent scatter data vary from one ionospheric region to another and rely on the experience of the analyst.

For example, as mentioned above, the Doppler shift of coherent echoes from $F$-region irregularities at high latitudes is known to be a good proxy for the line-of-sight plasma convection speed. Furthermore, it has been determined empirically that a broadening in the Doppler spectrum can be associated with the open/closed field line boundary. The Doppler shifts of coherent echoes from the ionosphere are often presumed to be mainly indicative of $\mathbf{E} \times \mathbf{B}$ drifts generally, although this association must be applied with care. Coherent echoes from ESF plumes are usually dominated by Doppler shifts indicative of ascent even though the $F$-region plasma is mainly descending during ESF. The discrepancy arises because the backscatter comes preferentially from ascending, depleted regions. In the equatorial electrojet, the Doppler shift is indicative not of the background electric field but of the polarization electric field, which is an order of magnitude larger. To the degree that neutral winds establish $E$- and $F$-region polarization electric fields, they also affect the Doppler shifts of coherent echoes, although extracting that information from the data generally requires a substantial modeling effort. The Doppler shifts of coherent echoes from Farley Buneman waves is closely related to the ion acoustic speed. In the auroral zone, this speed is elevated by heating related to the convection electric field, and so the electric field also influences the Doppler spectrum, albeit indirectly.

Coherent scatter is measured in all latitude regimes in the $D$, $E$, and $F$ regions. (At Jicamarca, coherent scatter has been detected at over 2000 km altitude!) Measurements are fast and finely resolved in space and time compared to many other classes of upper atmospheric and ionospheric observations. However, the interpretation of coherent scatter is not always rigorously defined. The real strength of the coherent scatter technique is realized when it is combined with observations from other instruments, including incoherent scatter radars and lidars especially. The coherent scatter can provide the regional context surrounding the regions where a lidar provides unambiguous information about atmospheric state variables. That information can feed back into the interpretation of the coherent scatter.

For example, among the more persistent sources of coherent scatter at all latitudes are irregular sporadic $E$ layers. These layers of metallic ions are through to be formed through the action of neutral wind shear. A leading theory about how the layers become irregular is that the wind shear also drives convective instability that deforms the layers. Once deformed, electrodynamic processes take over, leading to the generation of field-aligned irregularities (FAIs) and coherent scatter. Or so the theory goes. The existing radar datasets supporting research into sporadic $E$ layers barely capture the essential neutral dynamics, and so the theory remains speculative.

A wind temperature lidar could measure both the winds and wind shears necessary to form and destabilize the layers and the temperature profiles needed to assess the criterion for convective instability. A collocated ionosonde could establish the formation of the layers in the presence of wind shear, and a coherent scatter radar could identify layer structuring and subsequent FAI generation in a common volume. Thus, one of the oldest problems in radio and space physics could be resolved.
Another more fundamental issue is the ionospheric dynamo and the fact that coherent scatter radars are sensitive to dynamo-induced electric fields throughout the geospace system. Lack of detailed knowledge about the dynamo driver has made it difficult to capitalize on this information. A high-altitude Doppler lidar collocated with one or more coherent scatter radars would facilitate a quantitative assessment of dynamo theory and of the influence the MLT winds have on ionospheric stability, irregularity generation, and related aspects of space weather.