SPECTRAL INVERSION TECHNIQUES: PURPOSE, LIMITATIONS, AND IMPROVEMENTS.

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Why We Need Inversions: Modern studies of the solar atmosphere rely heavily on the accurate and consistent measurement of the physical conditions therein. As it is impossible (or impractical) to directly measure these conditions *in situ*, solar physicists must use remote sensing measurements, such as spectral line diagnostics. The detailed shape of these lines are determined by the physical state of the full atmospheric profile in which they are formed, as viewed by the observer. Because the remote sensing measurements result from a non-linear integration along the line of sight, inferring the true depth-dependent physical conditions requires calculating the inverse problem, i.e. inversion techniques. In order to investigate the finer details of the structure and dynamics of the solar atmosphere, it is imperative that these inversions be as accurate and reliable as possible.

Current Status and Limitations: With the exception of the most simplified approximations, such as the Milne-Eddington approach, most inversion techniques rely on an iterative scheme that combines the forward problem of a radiative transfer calculation and some form of least-squares or similar regression. Where this scheme struggles most is in the non-LTE regime, where simple approximations break down and the numerical problem becomes far more complex, resource-intensive, and ill-constrained. For studies of the chromosphere in particular, it is often necessary to treat hydrogen ionization in non-LTE, further increasing the numerical complexity and computational load to impractical levels. Furthermore, most existing inversion methods rely on the simplifying assumption of 1-D atmospheres in hydrostatic equilibrium, which breaks down in dynamic regimes. This can be especially problematic when including observations in the millimeter from ALMA, which is heavily dependent on the depth-dependent opacity from free electrons. Current inversions don’t take into account effects of time-dependent hydrogen ionization or complex 3-D illumination effects.

Avenues For Improvement: There are two general areas for improvement of inversion techniques. First, current inversion codes rely on multiple simplifying assumptions, such as 1.5-D and hydrostatic equilibrium, that imply conditions that we know do not actually hold in the dynamic solar atmosphere. Second, performing inversions of large datasets with the fully rigorous non-LTE radiative transfer formalism is prohibitively computationally expensive, especially when more complex physics such as PRD and Hanle effect are included.

We suggest that it would be scientifically advantageous if the community dedicated resources to improving the capabilities of spectral inversion codes. Some key avenues for advancement of these fundamental tools are:

Multidimensional inversions: improved treatment of the non-local radiation field of the surrounding atmospheric plasma, especially important for scattering lines or regions of high intensity gradients;.

Hanle and Zeeman diagnostics: These two quantum mechanical processes encode information on the magnetic field in the region of line formation, but are sensitive to different field strengths and local conditions. Inversion codes that can jointly leverage the information from both processes will be an important development.

Time-dependent effects: The solar atmosphere is a dynamic environment, particularly in the chromosphere, with multiple effects competing on different timescales. Crucially, impulsive heating effects, such as shocks and flares, cause local ionization and adiabatic expansion on sub-minute timescales, while the recombination timescale for hydrogen is tens of minutes. This and other effects can lead to a decoupling of the local electron density from Saha statistics, which in turn alters both the level populations of atomic species and the electron opacity for the millimeter continuum. Accounting for these effects is critical for accurate interpretation of both spectroscopic and continuum diagnostics in the dynamic atmosphere.

Neural networks/machine learning: Advances in computing methods promise to significantly speed up the inversion processing by avoiding much of the calculation needed for the iterative optimization. Neural networks and machine learning approaches have demonstrated orders of magnitude improvement in processing time, but lack the rigorous physical consistency required for modern scientific investigations. Efforts are needed to find ways to leverage these computational methods combined with the traceability necessary for effective interpretation.