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Key Points:
- High-altitude incoherent scatter experiments resumed at Jicamarca
- Electron densities measured to $L=2$
- Data comparable with magnetoseismic observations

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High-altitude incoherent-scatter measurements at Jicamarca

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Abstract In an attempt to reproduce experimental results obtained in the early days of operations, electron density profiles have been measured at the Jicamarca Radio Observatory at altitudes reaching L=2. The methodology involves using a combination of pulses, including pulses as long as 4 ms, and processing the data with matched filtering. The modern experiments are complicated by systemic, time-dependent bias in the noise estimators as well as by clutter from satellites and space debris, including a geosynchronous satellite. Ultimately, experiment performance comparable to what was achieved in the original experiments could be achieved and should be surpassed in future experiments when all four of the Jicamarca transmitters will be utilized.

1. Introduction

Located outside Lima, Peru, the Jicamarca Radio Observatory was constructed more than 50 years ago for the purpose of testing the emerging theory of incoherent scatter from ionospheric plasmas at a VHF frequency and at small magnetic aspect angles. The initial experiments produced unexpected results. It was anticipated, for example, that the autocorrelation functions measured at small magnetic aspect angles would have sharp, regular peaks at the gyroperiods of the ion species present and that Jicamarca would function like an ion mass spectrometer [e.g., *National Bureau of Standards*, 1963]. It was soon discovered, however, that ion Coulomb collisions largely destroy the ion gyroresonances [*Farley*, 1963b; *Dougherty*, 1964; *Woodman*, 1967]. At the same time, strong, nonthermal, field-aligned backscatter from plasma irregularities in the E and F regions was discovered [e.g., *Farley*, 1963a; *Balsley*, 1969; *Farley et al.*, 1970]. Within about a decade of operation, many of the salient aspects of radar science in the equatorial ionosphere fell into place, although discoveries continue to this day, most recently in the areas of lower-atmospheric effects on the equatorial ionosphere [*Chau et al.*, 2012], the effects of electron Coulomb collisions on incoherent scatter [*Milla and Kudeki*, 2011], and the interpretation of so-called “150 km echoes” [*Chau and Kudeki*, 2013; *Oppenheim and Dimant*, 2016].

One of the early predictions that turned out to be correct was that Jicamarca should be able to observe incoherent scatter at very high altitudes. This is because the plasma Debye length can remain smaller than Jicamarca’s 3 m radar scattering wavelength throughout the equatorial plasmasphere. In the early 1960s, Jicamarca used four transmitters with a 6% duty cycle, combined peak power of 4–5 MW, and pulse lengths as long as 5 ms to measure plasma density profiles over a very broad span of altitudes [*Farley*, 1966]. The mode was exploratory and meant to sketch the broad outlines of the heretofore unexplored space environment. It was also very demanding on equipment, personnel, and resources. As interest grew in more focused areas of interest including aeronomy, plasma instabilities, and space weather, and as the emphasis fell on measurements with higher spatiotemporal resolution, the high-altitude experiments were discontinued.

Farley [1991] summarized the results from the high-altitude runs in a review paper for the Eighth International Symposium on Equatorial Aeronomy held in 1990. The review presented results from a few multiday runs conducted in February, November, and December 1965. Electron density measurements were made through altitudes close to 10,000 km at times where the plasma density fell to a few thousand per cc and the topside density scale height became nearly infinite or even negative. The results exhibited considerable consistency from day to day although storm time variability was also evident.

The experiments described by *Farley* [1991] involved the use of multiple pulses with different pulse lengths and incorporated Faraday rotation measurements for absolute electron density estimation. However, details regarding the lengths and shapes of the pulses employed in the high-altitude experiments, the engineering characteristics of the square law detectors used for data acquisition at the time, and the manner in which the data were processed and combined into electron density profiles were not provided. It was not stated whether matched filtering was employed. The results were not accompanied by error analysis.

This paper represents the first attempt to repeat the high-altitude experiment at Jicamarca using modern equipment and methods and with better documentation. It is motivated by recent hardware improvements which restore the high-altitude capability. It is also motivated by growing interest in the coupled evolution of the thermosphere, ionosphere, and plasmasphere, particularly during storms. It is well known, for example, that ionospheric total electron content generally increases rapidly at low and middle latitudes during storms [e.g., *Mannucci et al.*, 2005]. Another consistently observed phenomenon is the formation of a plume of enhanced ionization extending from middle latitudes to high latitudes that maps into a corresponding density enhancement in the equatorial plasmasphere [e.g., *Foster*, 2013; *Goldstein et al.*, 2002]. Simultaneous measurements of ionospheric and plasmaspheric contents from the ground during storms could help elucidate the chronology and coupling of the underlying processes at work.

A specific goals of this research is to make reliable electron density measurements at high enough altitudes to overlap with magnetoseismic observations of plasmaspheric content. Magnetoseismic observations of field line resonances (FLRs) began a few years before Jicamarca opened and continue to this day (see, e.g., *Chi et al.* [2013] and references therein for discussion and review). Magnetometers in the North American chain cover L values from about 1.5 to 3.5. FLR detection is reasonably common during the day at L values of 2. The profiles published by *Farley* [1991] extended above $L=2$. Is comparable performance still possible given that there are new challenges with which to contend, notably clutter from satellites and space debris [*Committee for the Assessment of NASA's Orbital Debris Programs*, 2011]?

2. Methodology

The renewed high-altitude experiments made use of the full Jicamarca antenna in its on-axis (uniform-phase) pointing position. The aperture efficiency for this position is 0.63. The magnetic dip angle over Jicamarca has been decreasing steadily with time, and while this pointing position used to be oblique with respect to the geomagnetic field, it is now normal to it at an altitude of about 600 km. Two transmitters were used for the experiments to excite left- and right-circularly polarized emissions, respectively. The peak power was approximately 1 MW for both transmitters as measured using calibrated power meters. Both circular polarizations were received and sampled using digital receivers with filters matched to 100 μs square pulses. For power measurements, the power received in the two polarizations is simply added.

Pulse sequences were transmitted every 100 ms. A pulse sequence includes a long pulse followed after 80 ms by a short double-pulse pair. The mode used 64 contiguous sequences with 4 ms long pulses, 32 sequences with 2 ms long pulses, and 32 sequences with 1 ms long pulses, all constituting a single experiment. Following the transmission of 128 sequences, noise samples were taken in a transmitter-off interval lasting 2 s. The overall cycle time was therefore 14.8 s.

The double-pulse pairs consisted of 100 μs pulses transmitted on opposing circular polarizations with a time-varying gap that varied from 0 to 2.2 ms. The double-pulse is the standard technique used at Jicamarca for measuring incoherent scatter radar autocorrelation functions at low altitudes. Using opposing polarizations affords the possibility of independent electron density estimates via a Faraday rotation technique [*Farley*, 1969a; *Pingree*, 1990].

An experiment was run over a 24 h period on 31 May 2016, beginning at 15 LT (LT = UT + 5 h). Figure 1 shows relative transmitter power and receiver noise power measurements for the experimental interval in question. The transmitter power levels were nearly constant throughout the experiment. Signals from the directional couplers furthermore showed that transmitter power droop and frequency chirp were minimal, even for the 4 ms pulses. We therefore regard the transmit pulses as having ideal rectangular pulse shapes in the analysis that follows.

The received noise power meanwhile exhibited the familiar diurnal pattern for sky noise over Jicamarca's location. Calibrated noise power measurements have established the minimum and maximum sky noise temperatures to be approximately 5000 K and 40,000 K, respectively. We can expect experimental performance to be relatively poor for a few hours surrounding 0200 LT when the Milky Way was directly overhead.

Separate backscatter power estimates were derived from the short pulses as well as the 1 ms, 2 ms, and 4 ms long pulses and combined and plotted (in Figure 2 described below). The estimates were made using matched

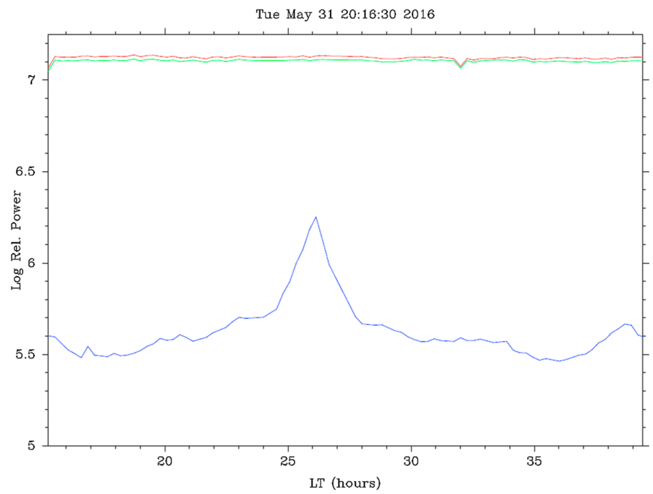

Figure 1. Relative power measured through the directional couplers (using 100 μs filtering) connected to each of the two transmitters (red and green curves) and from the sum of both receivers (using 4 ms filtering) during tx-off intervals (blue curve). A brief reduction in mains power occurred at about 8:00 LT.

filters, i.e., using synthetic filters with impulse response functions matched to the transmitted waveforms [e.g., *Papoulis*, 1984]. Noise samples were processed using the same filters as the samples containing signals.

Power was computed by squaring voltage samples and summing. In order to remove clutter due to satellites and space debris, we employed order statistics. In every range gate, we computed distinct power estimates from 64 contiguous time periods and then rejected the four highest and four lowest values before summing. The same algorithm was applied to noise-power estimates as to power estimates containing signals. The same method is used routinely for topside data processing at Jicamarca [*Hysell et al.*, 2009].

The aforementioned algorithm works well with most kinds of clutter but is ineffective against very long-lived clutter sources, notably geosynchronous satellites. On three occasions, clutter from a geosynchronous satellite was visible in the data, range aliased to an apparent range of about 5800 km. One of these occasions lasted for about 1/2 h. The time intervals in question had to be removed from the data set.

Noise-power estimates were subtracted from each of the power profiles which then underwent a correction to remove the effects of the square of the radar range. The power profiles were then combined in the same figure using normalization constants to compensate for the different waveform pulse lengths and experimental duty cycles. What resulted are profiles of range-corrected backscatter power, which we regard to be a proxy for electron density. In most incoherent scatter applications, the backscattered power is proportional to the electron number density divided by a factor of unity plus the electron-to-ion temperature ratio. At VHF frequencies and at small magnetic aspect angles, the temperature scaling is somewhat different than this and is less sensitive to the T_e/T_i ratio [see, e.g., *Rodrigues et al.*, 2007].

Error analysis was performed according to the principles laid out by *Farley* [1969b, 1972]. The scattered signal and the noise are stochastic. Formally, the signal and noise powers are the expectation of the squares of the signal and noise voltages on the antenna, respectively. We approximate the expectation with a time average, but this estimator imposes an error, and the error manifests as the fluctuations. The errors depend on SNR and are highly correlated in range, explaining the discontinuities between the different curves.

Finally, an independent measurement of the electron density profile was derived from the Faraday rotation of the short-pulse measurements. We use only the zero lag of the double-pulse data for this measurement. The measurement is absolute but is not particularly robust and is confined to a relatively narrow range of altitudes near the *F* peak. On the basis of the Faraday rotation data, we developed a unitary (one time) normalization constant which we applied to all the power profiles to convert from corrected power to electron number density. For detailed information about the performance of the Faraday rotation measurement, see *Farley* [1969a] and *Pingree* [1990].

3. Observations

Results of the analysis described above are shown in Figure 2. The incoherent integration time for the profiles is approximately 3 h. The violet, green, blue, and cyan curves represent data from the short, 1 ms, 2 ms, and 4 ms pulses, respectively. We make no attempt to deconvolve or compensate for the different ambiguity functions of the different pulse modes. The longer the pulse length, the more sensitive the measurement but the poorer the range resolution. The pulse length controls the tradeoff between fluctuation and bias in the

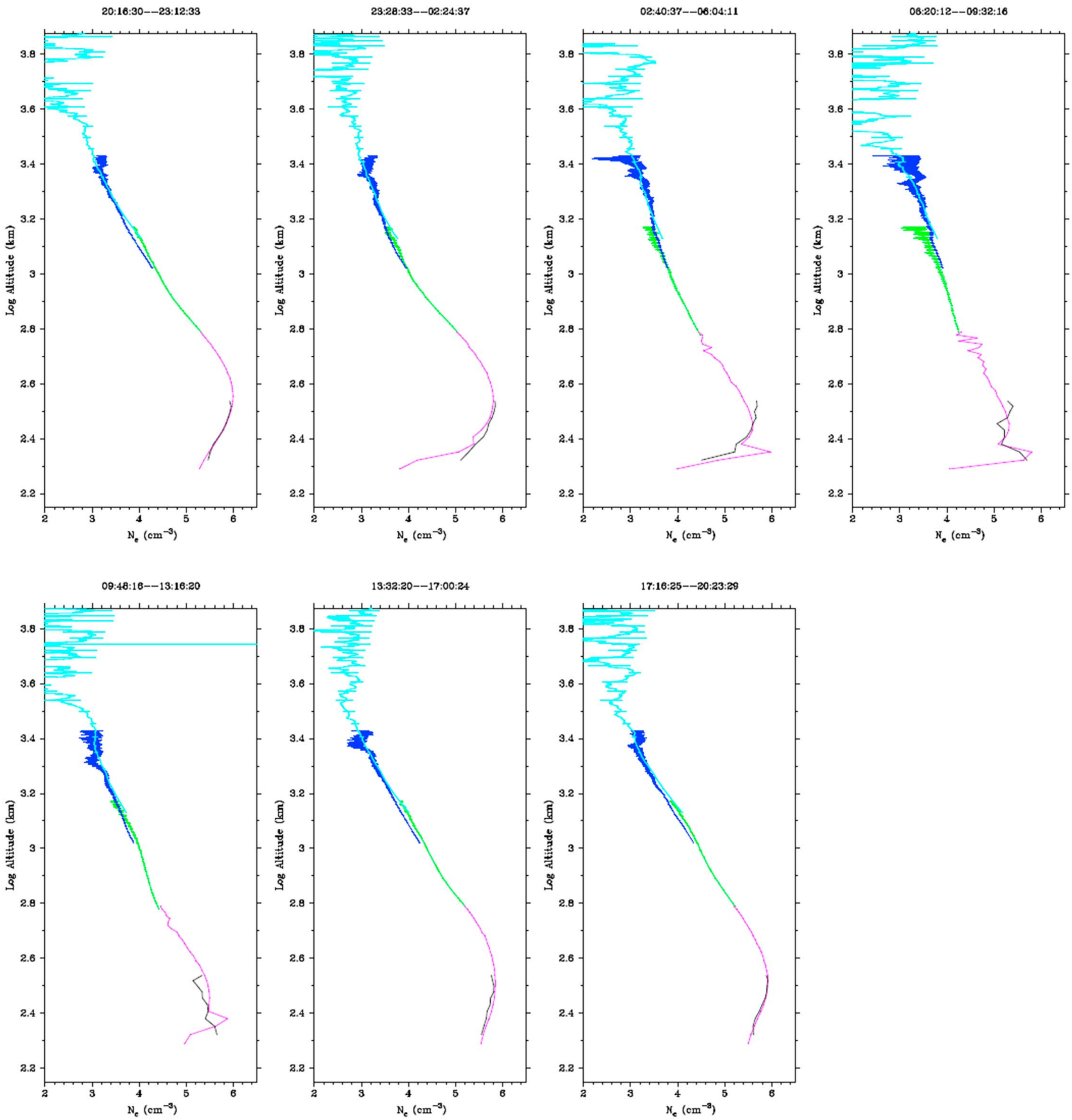

Figure 2. Corrected power profiles spanning the duration of the high-altitude echo experiment. The violet, green, blue, and cyan curves are based on measurements involving short, 1 ms, 2 ms, and 4 ms transmitter pulses, respectively. The black curves are derived from Faraday rotation measurements and used to normalize the other curves. Error bars are drawn through every twentieth range.

power estimators. As the altitude increases, a favorable tradeoff is given by pulses with increasing lengths. We also do not compensate for small differences in the transmitter power between different pulse lengths.

The peak at low altitudes in the nighttime profiles is due to clutter—coherent scatter from field-aligned plasma density irregularities associated with bottom-type spread *F* layers [*Woodman and La Hoz*, 1976]. Coherent scatter also degrades the Faraday rotation experiment which can become unreliable at night. The overall experiment benefited from the absence of topside spread *F* which is relatively uncommon in late May at Jicamarca.

As was the case in 1965, the profiles shown here have the smallest statistical fluctuations around noon and in late afternoon when the sky noise temperature is near minimum (in the case of May data) and when the electron densities are greatest. Profiles from the interval 1928–2224 LT and 0932–1300 include usable electron density estimates up through about 6300 km altitude; above that, the relative RMS deviations in the density estimates are essentially 100%. We also find that the topside density profiles often exhibit consistent power law behavior over very broad spans of altitudes. Unlike the 1965 measurements, which produced no density measurements as low as 1000 per cc, all of the profiles shown here tend to about 1000 per cc at the highest altitudes where reliable measurements exist. The dynamic range of the present experiment appears to be superior to that of the original.

The present data also do not indicate negative topside scale heights and the tendency for electron density to increase with altitude systematically anywhere in the topside. In the course of conducting this research, we have discovered that the transmitters at Jicamarca have a tendency to start producing noise, shot noise most likely, sometime after pulse transmission ends. This can appear as a system noise temperature that increases with range. Once detected, the problem can be mitigated in hardware and in software. If left unmitigated, the problem would tend to produce the kind of features that were sometimes present in the 1965 results. While the hardware (except for the antenna) was entirely different in the 1960s, we can speculate that a similar problem may have been present back then.

Lastly, we consider the possibility of measuring state parameters other than electron density at high altitudes. Figure 3 (left) shows representative lag profiles for some of the high-altitude data acquired using 4 ms pulses. Here we show only values out to lags of 1.8 ms. Error bars are superimposed. These become rather large above about 3000 km altitude. The routine topside mode at Jicamarca incorporates data like these into a full-profile analysis which yields estimates of electron density, electron and ion temperature, and light-ion composition up to about 1500 km altitude [*Hysell et al.*, 2015]. Here we consider the prospects of making inferences even higher.

The figure shows lag profiles as opposed to autocorrelation functions. The former are related to the latter through two-dimensional convolution with so-called range-lag ambiguity functions [e.g., *Nygrén*, 1996]. There is also a triangular taper with lag time inherent in the lag products shown here that must be considered.

To the extent that (1) the ionospheric state parameters are not varying strongly with range, (2) the correlation time of the echoes is short compared to the pulse length, and (3) correlation time is long compared to the sample time, the aforementioned differences between the measured lag products and the autocorrelation function of the medium can be neglected, at least for the purposes of a rough assessment of data quality. Note that correlations across lags and altitudes have been neglected in the error analysis associated with this simple test.

Figure 3 (right) shows electron temperature estimates made by fitting the lag products directly to incoherent scatter theory. We assume equal electron and ion temperatures and a purely protonic plasma. Routine topside measurements at Jicamarca generally fail to register significant amounts of atomic ions at 1500 km altitude [*Hysell et al.*, 2015]. Trace amounts of atomic ions at the altitudes in question here would bias the temperature estimates somewhat but would not significantly impact the sensitivity test we are attempting. The results of the fitting are consistent with expectations for the given time and altitude and suggest that usable state-parameter estimates are available above 2000 km altitude. In the future, we can incorporate longer pulses on routine full-profile topside analysis mode.

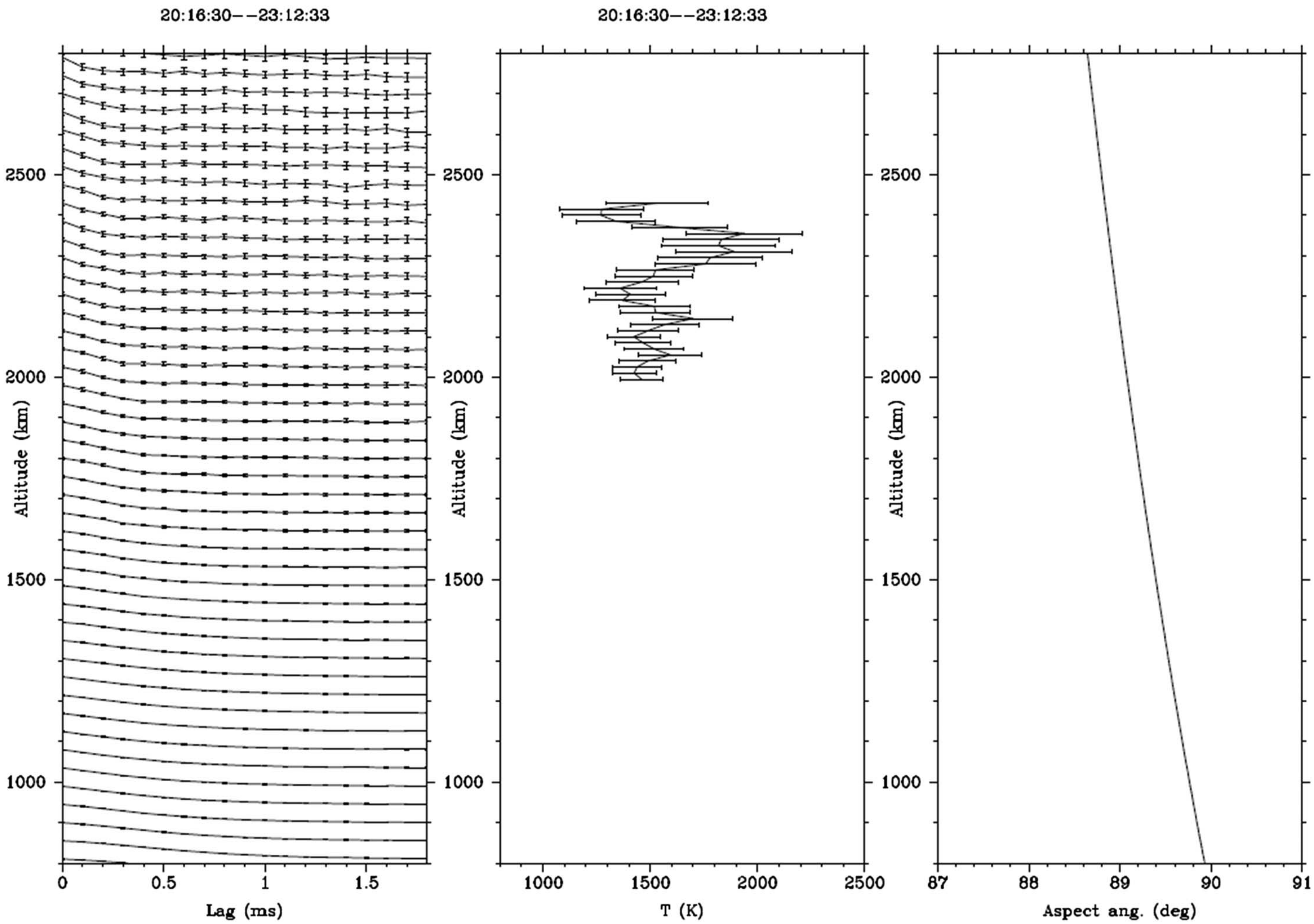

Figure 3. Topside data corresponding to the 4 ms pulse. (left) Incoherent scatter lag products versus range and lag. (middle) Electron temperature estimated obtained by direct nonlinear least square fitting of incoherent scatter theory to the lag products (see text). (right) Magnetic aspect angle for the on-axis antenna position versus altitude.

4. Summary and Conclusions

We have measured electron density profiles at altitudes up to about $L = 2$ using very long uncoded pulses at Jicamarca. The performance of the technique appears to be comparable to what was achieved in the early history of the observatory when four transmitters were available.

Matched filtering generally only improves the signal-to-noise ratio so long as the correlation time of the target remains longer that the filter impulse response time. The incoherent scatter spectrum being measured here as a correlation time of the order of 1 ms near the *F* peak and less in the topside where protons predominate. The use of longer filter impulse response times (i.e., 2 and 4 ms) in the present analysis mainly just degraded the range resolution of the measurements somewhat while increasing the signal-to-noise ratio only slightly. The latter effect is due to the removal of some low-level spurious interference. Very similar results to those presented here were obtained by applying a 1 ms boxcar filter to signals from all the long pulses and renormalizing the estimated power profiles accordingly. The particular filtering scheme employed in the historical experiments was therefore not critical to the results.

Even more sophisticated methods for processing long-pulse data are now available. One option is the range-Doppler processing method described by *Vierinen et al.* [2016] and applied to plasma-line observations made using the Sondrestrom incoherent scatter radar. Another is the full-profile analysis introduced by *Lehtinen* [1986] and *Holt et al.* [1992] and employed routinely now for topside investigations at Jicamarca [*Hysell et al.*, 2015].

That the power profiles plotted from the original experiments were continuous and unbroken over the entire span of altitudes suggest that they were drawn by an artist with a French curve rather than by a plotter. We therefore refrain from assigning much significance to the level of fluctuations in the curves. Small discontinuities in the profiles in Figure 2 reflect the fact that the range resolution of the component curves differ and are unavoidable (absent the application of inverse methods). Such methods will be explored in subsequent studies.

For the first time in many years, four transmitters are once again available for use at Jicamarca. Although they were not all utilized in the present experiments, they can be in future ones. The extra 3 dB of sensitivity should make it possible to measure electron densities at $L=2$ routinely and up to 10,000 km altitude occasionally. Experiments using pulses longer than 4 ms should also be possible thanks to recent improvements in the power supplies.

The signal-to-noise ratio near and above $L=2$ is always very small, making accurate noise estimation and subtraction vital to a successful experiment. Recent investigations at Jicamarca have uncovered small but potentially important time-varying sources of noise that could easily bias the high-altitude experiments. Some of the same noise sources could have been present but might have gone undetected in the early days of operations at Jicamarca. These could account for the infinite and negative topside scale heights reported in some of the earlier high-altitude experimental results.

A modern-day source of contamination is radar clutter from satellites and space debris. A previously unsuspected source of clutter was found in the current experiments to be geosynchronous satellites. The radar clutter thus produced was very long-lived and had a signal-to-noise ratio of about unity in the 4 ms pulse data at an apparent range of about 5800 km. We have no recourse but to remove such clutter manually.

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