Reports

Spectral Line Interferometry with Independent Time Standards at Stations Separated by 845 Kilometers

Abstract. *An upper limit of 0.02 second of arc has been determined for a hydroxyl radical (OH) emission region associated with the radio source W3, with the use of a Michelson interferometer consisting of two radio telescopes 845 kilometers apart. Timing was provided at the stations by independent atomic frequency standards. The 1665-megahertz radiation was translated to video frequency and recorded digitally on magnetic tapes which were later processed by computer, yielding fringe phase and amplitude as a function of frequency over the received bandwidth.*

The hydroxyl radical (OH) emission sources associated with many HII regions exhibit remarkable polarization properties, anomalous intensity ratios, and narrow line widths (*1*). The individual lines originate in regions of small angular size, as shown by interferometer measurements (*2*). A recent measurement (*3*), with the 120-ft (37-m) telescope of the M.I.T. Lincoln Laboratory Haystack Microwave Research Facility and the Agassiz 60-foot (18.5-m) telescope of Harvard College Observatory as a 74,400-wavelength interferometer showed that the strongest components of the emission complex associated with the radio source W3 (IC1795) were unresolved, although the source positions for individual lines were not coincident; the Jodrell Bank-Malvern group (*4*) showed that the strongest feature, at a radial velocity of −45.1 km per second, is unresolved with a baseline of 700,000 wavelengths. Further increases in baseline length have been made possible by the advent of highly stable, atomic frequency standards; results were reported by the Algonquin-Penticton group (*5*) and by the National Radio Astronomy Observatory (NRAO)-Arecibo group (*6*) who have observed fringes from continuum sources with base lines of 4.6×10^6 and 4.6×10^5 wavelengths, respectively. Rather than deriving local oscillators from a common reference and transmitting the received intermediate-frequency signals to a common point as in conventional interferometry, the local oscillators at each station are locked in phase with an atomic frequency standard. The received signal is converted to video frequencies and then recorded, with time information, on magnetic tape in digital or analog form. The records are later reduced at a data-processing center, and fringe amplitudes are derived by cross-correlating the two sets of measurements.

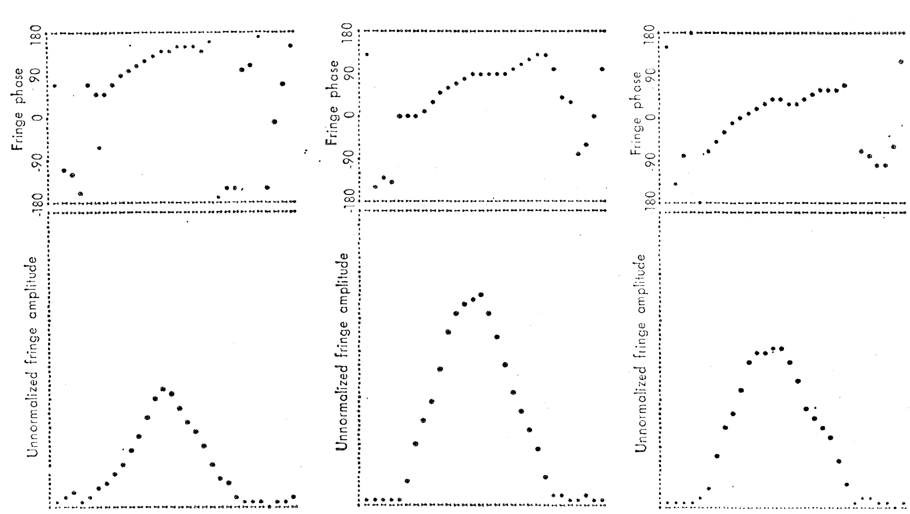

Fig. 1. Sample computer outputs of fringe amplitude and phase as a function of frequency for the line of W3 at −45.1 km per second. Frequency axis is horizontal and covers a total bandwidth of 6 khz with an effective resolution of 500 hertz. The records shown are for relative frequency offsets of 0.0, 0.025, and 0.050 hertz, and an integration time of 20 seconds.

Our results were obtained with the use of the Haystack 120-foot (37-m) telescope and the 140-foot (42.5-m) telescope of the National Radio Astronomy Observatory. The separation of the two instruments is 845 km, or 4.7×10^6 wavelengths at 1665.4 Mhz, which corresponds to a fringe spacing of 0.044 second of arc. The Haystack station used a hydrogen frequency standard (*7*) as a frequency reference, and data were recorded on magnetic tape through the U490 computer that services the antenna. A rubidium frequency standard (*7*) was used at the NRAO, and data were recorded on one of the two magnetic tape systems developed by the NRAO-Arecibo group. In both recording systems, the received signals were clipped, sampled, and recorded digitally. Full spectral information is thus retained, except for a scale factor. The absolute value of the power spectrum is easily recovered, however, when the system noise temperature is known and the total power is measured, as it was in this experiment. Relative timing of the two stations is important, although not as critical as in wide-band continuum measurements, because of the narrow linewidths, which are typically of the order of 2 khz. The master Loran C station at Cape Fear, North Carolina, was used to set our station clocks, and microsecond-timing accuracy was achieved. To compensate for the high rate at which a source travels through the interference fringes, which could be several hundred hertz, the local oscillators were set to different previously computed frequencies to rotate the fringes with the source. An alternate way of looking at the fringe compensation is to regard the fringe rate as arising from the beating between the two signals, in view of the fact that they undergo different Doppler shifts on the earth's rotation. The individual local oscillator offsets thus compensate for this differential Doppler shift, as well as for the common corrections due to the earth's orbital motion and the motion of the sun with respect to the local standard of rest.

Observations were conducted from 8 to 12 June 1967. Observing bandwidths of either 6 or 120 khz were used, and a variety of OH-emission sources were observed. Circularly polarized feeds were used on both antennas, and either sense of polarization could be selected. The reductions completed so far have concentrated on the strongest feature in the 1665 Mhz spectrum of W3. This line has a radial velocity of −45.1 km per second with respect to the local standard of rest and is strongest when right, circularly polarized radiation is received. The 6-khz bandwidth is wide enough to display the complete line profile, and the presence of the line on each computer tape was easily verified by taking the Fourier transform of the autocorrelation function for each set of data.

The fringe phase and amplitude of the interferometric combination was derived by the method outlined by Rogers (*8*). The recorded video signals were cross-correlated at delay intervals (τ) centered on the expected geometric time delay for the observed source. The cross-correlation function was taken over periods of 0.02 second, which was short compared to the apparent fringe period. The time dependence of the cross-correlation function was removed through multiplication by a trial function, equivalent to a local oscillator offset. This operation, when the trial function is correctly chosen, converts the cross-correlation function to a time-independent function, $R(\tau)$; the fringe amplitude and phase can be derived as a function of frequency from the complex Fourier transform. The apparent local oscillator offset can be caused by a real difference between the two frequency standards or by an error in the adopted base line. The two effects can be separated by observation of the diurnal variation of the frequency offset. An incorrect frequency offset diminishes the apparent fringe visibility; therefore, a range of offsets was covered to make certain that the fringe visibility was maximized.

From the examples of the computer output (Fig. 1), it is clear that the offset can be determined to better than 0.01 hertz. This corresponds to an accuracy of six parts in 10^{12} in measuring the apparent frequency difference, and with sufficiently long integration the accuracy could be significantly improved. Over the 4-day observing period, the offset correction varied less than 0.1 hertz. The fringe visibility was derived from taking autocorrelation spectra of each record and comparing the observed fringe amplitude with the expected value.

The line of W3 at −45.1 km per second was observed over an hour-angle range of 14 hours, and the fringe visibility is 1.0 ± 0.2 over the entire range. We can find no evidence of resolving the source, thus implying an upper limit to the apparent size of 0.02 second of arc, for the equivalent uniform disk. If the apparent size refers to the true size of the OH source, its linear dimension would be less than 34 astronomical units at a distance of 1700 parsec for W3.

In addition to the scientific potentiality, the method promises to be a powerful technique in checking frequency standards and clocks. The best timing accuracy can be achieved with the widest bandwidths; however, the narrow bandwidth of the OH lines aids greatly in establishing the first timing estimates, in view of the fact that millisecond timing is sufficiently good as a first approximation. Successively better approximation can then be made by widening the bandwidth to include lines at other velocities. The OH lines of W3 are sufficiently strong to permit the use of smaller antennas for such timing applications, and a dish diameter of 9 m should be adequate.

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9. We thank G. M. Hyde, who provided time and frequency standards at the Haystack Facility (HF); N. M. Brenner for assistance with the programming at HF; the staff of the computation center of HF, where data reduction was carried out; the observing staffs of both the NRAO and HF; T. L. Wilson for help in making the observations; and S. Weinreb, D. S. Heeschen, M. L. Meeks, and P. B. Sebring for encouragement. Supported in part by NASA (grant NsG-419) and by NSF (grant GP-7046). Lincoln Laboratory is operated by M.I.T. with the support of the U.S. Air Force; NRAO is operated by Associated Universities, Inc., under contract with NSF.

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Bermuda's Southern Aeolianite Reef Tract

Abstract. *The outer reef on the explored southeast margin of the Bermuda platform is a submerged dune ridge thinly veneered with encrusting organisms. Aeolianites were deposited on what appears to be an older truncated surface, the reef-front terrace, now submerged to a depth of about 18 meters. Underwater examination reveals relict features of probable solutional origin that honeycomb the aeolinite and that have undergone only minor modification by erosion since the last eustatic rise of the sea. Submarine planation, even in this marginal area of reef growth, is a relatively slow process.*

The Bermuda platform, bounded by 32°14′ and 32°29′N and 64°37′ and 65°00′W, is located at the northern limit of reef growth in the North Atlantic Ocean. Conditions for reef development are now marginal (winter temperatures drop to about 18°C); a drop of only several degrees for a short continuous period would terminate the present sparse growth of corals and related reef organisms (*1, 2*).