NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROGRAM

VLA TEST MEMORANDUM NO. 131

CHOICE OF NORMALIZATION FOR SPECTRAL LINE OBSERVATIONS

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I. Introduction - A List of Problems

The VLA correlator produces an unnormalized cross correlation function. This is related to a cross spectral function by a Fourier transform. Eventually the desired entity is a sky map calibrated in brightness temperature or equivalent units. The cannonical intermediate is a cross spectral function calibrated in units of spectral flux density - conceptually the source flux times the complex normalized visibility function. This is hereafter referred to as the cross power spectrum.

The current method of achieving this is to calibrate a mean (as a function of frequency) system gain using calibrators, and then to make a lengthy observation of a very strong source to determine, for each baseline, the variation of gain as a function of frequency (a "passband observation"). This procedure is laborious, time consuming, and fraught with possibilities of error. The question addressed here is whether an improvement in the procedure can be made by use of the additional information provided by the correlator - the autocorrelation functions for each individual IF.

Before discussing this however, it is worth condsidering the types of observations the VLA will be doing in spectral line mode, and consider the requirements of each. Therefore the following list:

1) Strong masers (OH, H_2O) - exact fluxes are usually unimportant; phases, especially relative phases, may be important; high dynamic range in frequency (weak emission at a frequency near a very strong line) may be important.

2) Molecular emission from cold clouds - signal-to-noise ratio is so low that exact calibration (i.e. better than ~5%) of any kind is unnecessary.
3) Weak masers (e.g. extragalactic OH) - same remarks as 2).
4) Extragalactic HI - same remarks as 2).
5) Strong HI absorption of small sources - results are insensitive to calibration; one usually wants to know only if absorption is present and its velocity and width if so.
6) Absorption in other lines - a careful amplitude calibration is often necessary because the absorption may be very weak.
7) HI absorption of extended sources - the observations will often be limited by calibration accuracy.
8) Weak HI absorption - the necessity of as accurate as possible amplitude calibration is complicated by the presence of strong, spacially smooth but frequency dependent HI emission in the antenna beam.
9) Recombination lines and other weak lines in strong extended sources - calibration is crucial; as careful a job as possible is essential in both amplitude and phase.

II. Procedure and Observations

The correlator calculates the auto correlation function of each IF as well as the cross correlation functions of each pair of IF's. In the standard system, only the lag 0 autocorrelation is used; the mean of the two lag 0 correlations is used to divide (normalize) the cross correlation function, which is then Fourier transformed to produce the cross power spectrum. Ken Sowinski produced for us a special system to test an alternative normalization. This system Fourier transforms the autocorrelation functions to produce the IF power spectra as well as the cross power spectra. The cross power spectra are then divided by the geometric mean of the two IF power spectra. The resulting spectra are hereafter referred to as normalized cross power spectra, and the spectra produced by the standard system as unnormalized cross power spectra. For facility of implementation, the clipping correction was not applied, resulting in systematic deviations of the computed IF power spectra from the actual.

The expectation is that the normalized cross power spectra on a white point object will be to flatten its spectrum and to remove many, but not all, gross characteristics of the IF. The question of greatest interest is whether the remaining effects are time stable or not.

For an example of an effect that one might, at first encounter, expect to be corrected by normalization, but on further reflection proves more complex, consider the Gibbs phenomenom. This is the "ringing" of the spectrum at roughly a two channel period due to truncation of the cross correlation spectrum at some finite delay. As we compute it, the Gibbs phenomenom will appear to be a function of the phase on the baseline. To show this, consider the simplest possible case - a rectangular passband, Nyquist sampled, with flat phase. If the phase difference between the two IF's is ϕ, the cross correlation function at lag τ is

$$C\ (\tau) = R_e\ \{e^{i\omega_0\tau/2+\phi}\}\ \frac{\sin\omega_0\tau/2}{\omega_0\tau/2}$$

where the bandpass is flat from 0 to ω_0 and 0 elsewhere.

$$C(\tau) = \cos\ (\omega_0\tau/2+\phi)\ \frac{\sin\omega_0\tau/2}{\omega_0\tau/2}$$

Nyquist sampling is given by

$$C_n = C(\ \frac{n\pi}{\omega_0\tau}\ ).$$

For $\phi = 0$ (or autocorrelation)

$$C_n = \begin{matrix} 1 & \text{for } n = 0 \\ 0 & \text{elsewhere} \end{matrix}\ .$$

The Fourier transform of the C_n in this case obviously does not exhibit the Gibbs ripple. For $\phi = \frac{\pi}{2}$

$$C_n = \begin{matrix} 0 & \text{for } n \text{ even} \\ \frac{2}{\pi}\ (-1)^{\frac{n-1}{2}}\ \frac{1}{n} & \text{for } n \text{ odd.} \end{matrix}$$

Numerical calculation verifies that the transform of this shows the Gibbs phenomenon at about the $1/N_{chan}$ level.

Observations were made of strong sources to determine how well normalization flattens the passband and to investigate stabilities of both the normalized and unnormalized spectra. For the latter purpose, 3C273 was observed for sufficiently long periods to ensure a single channel signal-to-noise ratio of several hundred to one (10 minutes for 400 KHz channels, 90 minutes for 25 KHz channels). For convenience, 8 antennas (a mixture of long and medium baselines) were used for all observations, and 128 or fewer channels were used for all.

Typical results for the normalized spectra are given in Figure 1. This shows that the method works reasonably well for bandwidths of 6.25 MHz and less (channel widths 100 KHz or less). At 12.5 MHz it somewhat flattens the bandpass but may actually enhance the ripple. Why it should do so is not understood; the phenomenon is illustrated in Figure 2 (the baseline in Figure 1 is atypically good). The ripple appears to be worse on the normalized spectrum than the unnormalized about 60% of the time (20 of 32 examples).

At the two widest bandwidths, the normalization does not even flatten the bandpass. At all bandpasses it is clear that only the center 3/4 of the channels are flat and useful. In most cases, the spectra drop off at the ends, though in a few cases a spike at the end is observed. The cause of this is not clear - one would think a properly corrected spectrum would be flat all the way across, with an increase of noise at the ends - but the phenomenon is probably caused by the omission of the clipping corrections. At the narrower bandpasses, the correction is sufficiently good to eliminate the need for a bandpass calibration for those problems insensitive to calibration errors.

A prime object of this investigation was to determine if this means of normalization would increase the stability of the passband as well as flattening it. The horrible examples shown in Figure 3 should convince one that the technique is not a panacea for sick IF's. Note that in one example the unnormalized spectrum shows an even more extreme change; in the other it shows much less.

A particularly interesting phenomenon is shown in Figure 4. Using antenna 11 as a reference antenna, one concludes that antenna 28 has about a 3% slope and antenna 24 has none - so antenna 28 has a 3%

slope relative to antenna 24. Using antenna 16 as a reference antenna, antenna 28 has a 7% slope and antenna 24 has a -2% slope - so antenna 28 has a 9% slope relative to antenna 24. This is an amplitude closure error! Further, it is a closure error not susceptable to the usual explanations. They are:

1) Frequency structure finer than the channel width - a general ripple covering 3 MHz with a ripple wavelength less than 25 KHz seems excessively improbable.
2) Variation of phase or gain in different fashions on different antennas on a time scale shorter than the integration interval - should be removed by the sum channel normalization with which the plots were made.
3) Errors in the quadrature network - not used during spectral line observations.
4) Gross variations of bandpass shape during the integration interval - the effect is visible on individual five minute records, which resemble each other fairly closely during the scan.

We are unaware of a reasonable explanation for this phenomenon.

As noted in Section I, among the problems most sensitive to accurate calibration are HI absorption - either weak absorption or absorption in extended sources. Both cases present a unique problem. To convert a measured spectrum to a true cross power spectrum requires two steps: Passband correction and system temperature correction. In the unnormalized case, the system temperature correction is measured in the band fed to the sampler. This is done by the synchronous detector in the T5 Module, although software for applying it is not yet available. In the normalized case, however, the system temperature correction must be measured in each synthesized channel. It is not acceptable to use the average system temperature over the band, because this may change significantly because of the contribution of the radiation from galactic hydrogen. Figure 5 illustrates this effect. The normalized spectrum of 3C147 shows a broad dip which would be easy to interpret as 5% absorption. The fact that it is not present in the unnormalized spectrum indicates that it is not absorption, but reflects the fact that galactic HI line radiation is raising the system temperature in this frequency range. This figure dramatically illustrates that it is unacceptable to simply make the passband normalization in this way without being able to recover this information. Possible ways around the difficulty are:

1) Provide a switch to turn the correction off.
2) Record the autocorrelation spectra along with the cross correlation spectra to be able to convert back to unnormalized spectra post facto.
3) Record autocorrelation spectra on calibrators, read them back and apply them on unknowns.
4) Record autocorrelation spectra at a different frequency on source.
5) Synchronously detect the autocorrelation spectra so that the system temperature is measured in each channel.

Option 2 increases the data recording appreciably, and considerably increases the complexity of off-line software. Option 3 is likely to be confusing to observers - they must make sure their calibrator is in a low emission area, and must be aware that they must collect a calibrator observation before the unknown, with the same choice of bandwidth, antennas, IF and channels. Although single dish observers have been keeping this sort of thing straight for years, there are a great many additional things to watch at the VLA, and this is likely to be an intolerable burden.

Option 4 is nearly as confusing as three, and suffers the additional question of whether front end effects might not affect bandpass significantly.

Option 5 shows promise. The detected cals are about 6% of system. Normalization in this fashion would therefore not add appreciable noise to the observation if the correlation were less than ~1%. The loss of signal-to-noise ratio is probably not important for observations of stronger sources - they will probably be calibration limited anyway. However, so much theoretical, hardware, and software work would be involved in this approach that it is not practical to consider it in the near future.

III. Conclusions and Recommendations

The autocorrelation function normalization is exceedingly convenient. If reasonable care is taken about delays, it provides a sufficiently good passband to eliminate the need for a seperate passband calibration for many types of observations: cold cloud molecular emission, weak masers, extragalactic HI, strong HI absorption of small sources, and perhaps strong masers (where accurate fluxes are not necessary) and strong molecular lines from HII regions. It is an acceptable technique for other observations which still require a bandpass calibration (to correct phases if nothing else): absorption in lines other than HI and recombination lines. It adds nothing to these problems except a more pleasing quick look, but it probably does not harm them. It is an unacceptable technique for delicate HI absorption measurements without one of the enhancements suggested in Section II.

The ability to eliminate the passband calibration for a fairly wide selection of observations appears to make the capability of normalizing worthwhile. The inability of simple normalization to properly handle HI absorption dictates that it be switch selectable, perhaps by a different set of mode codes. The various possible uses of the switching cals should be investigated on a longer timescale.

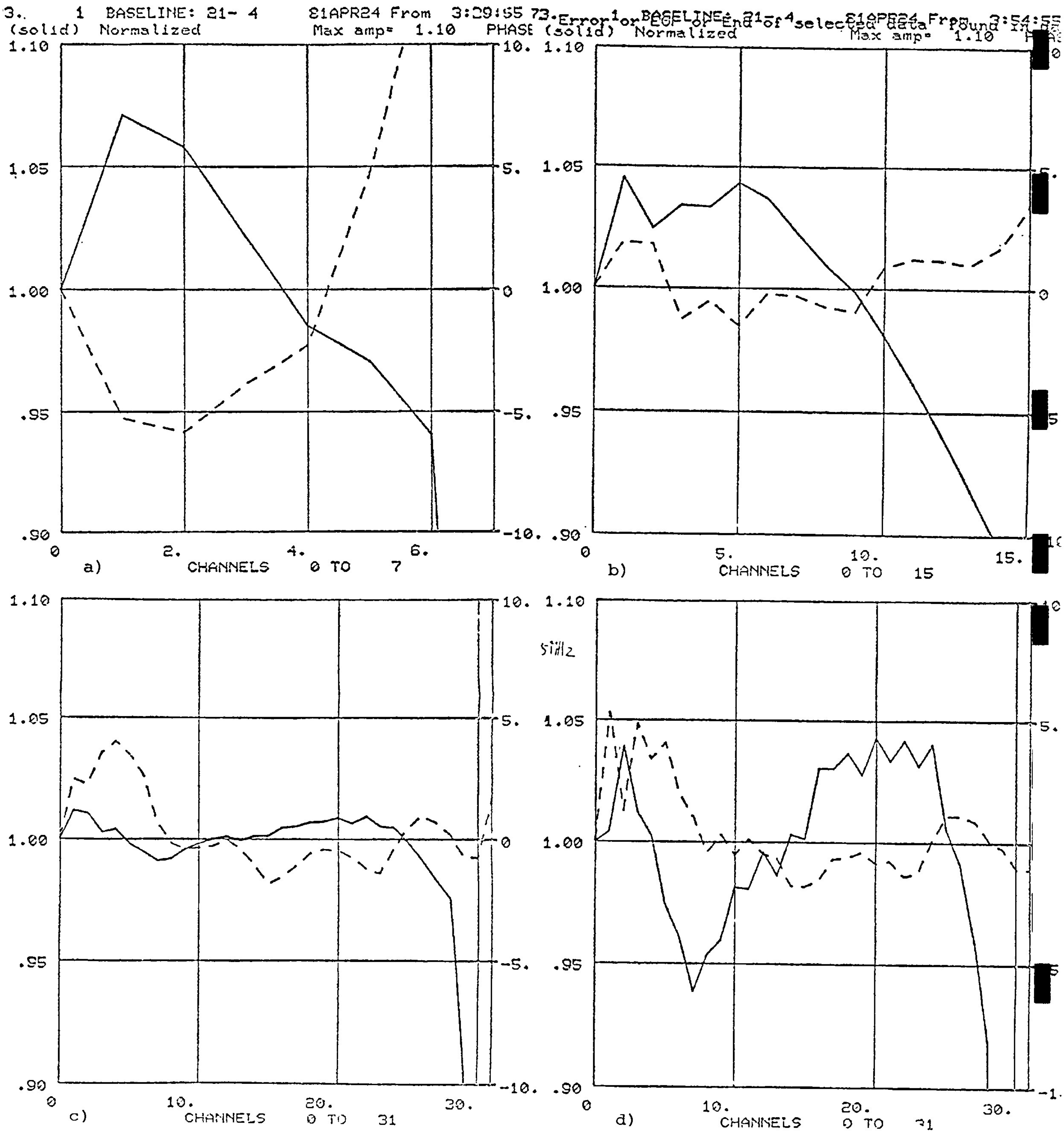

Figure 1. Source: 3C273, Baseline: 4-21. Solid line, lefthand scale are amplitude, dotted line, right hand scale are phase. a) 8 channels, 50 MHz bandwidth, normalized. b) 16 channels, 25 MHz bandwidth, normalized. c) and d) are both 32 channels, 12.5 MHz bandwidth; c) is normalized, d) unnormalized.

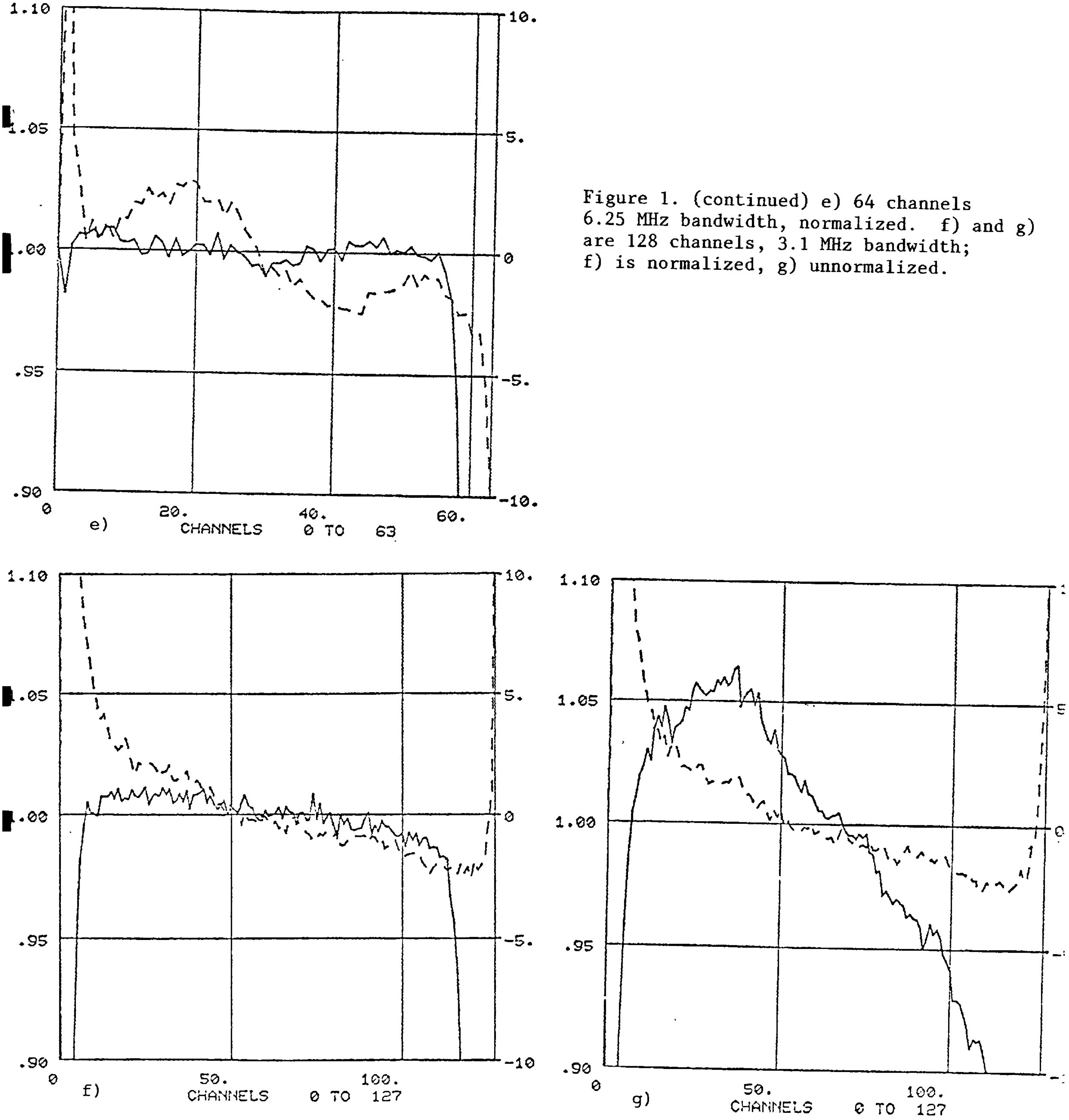

Figure 1. (continued) e) 64 channels 6.25 MHz bandwidth, normalized. f) and g) are 128 channels, 3.1 MHz bandwidth; f) is normalized, g) unnormalized.

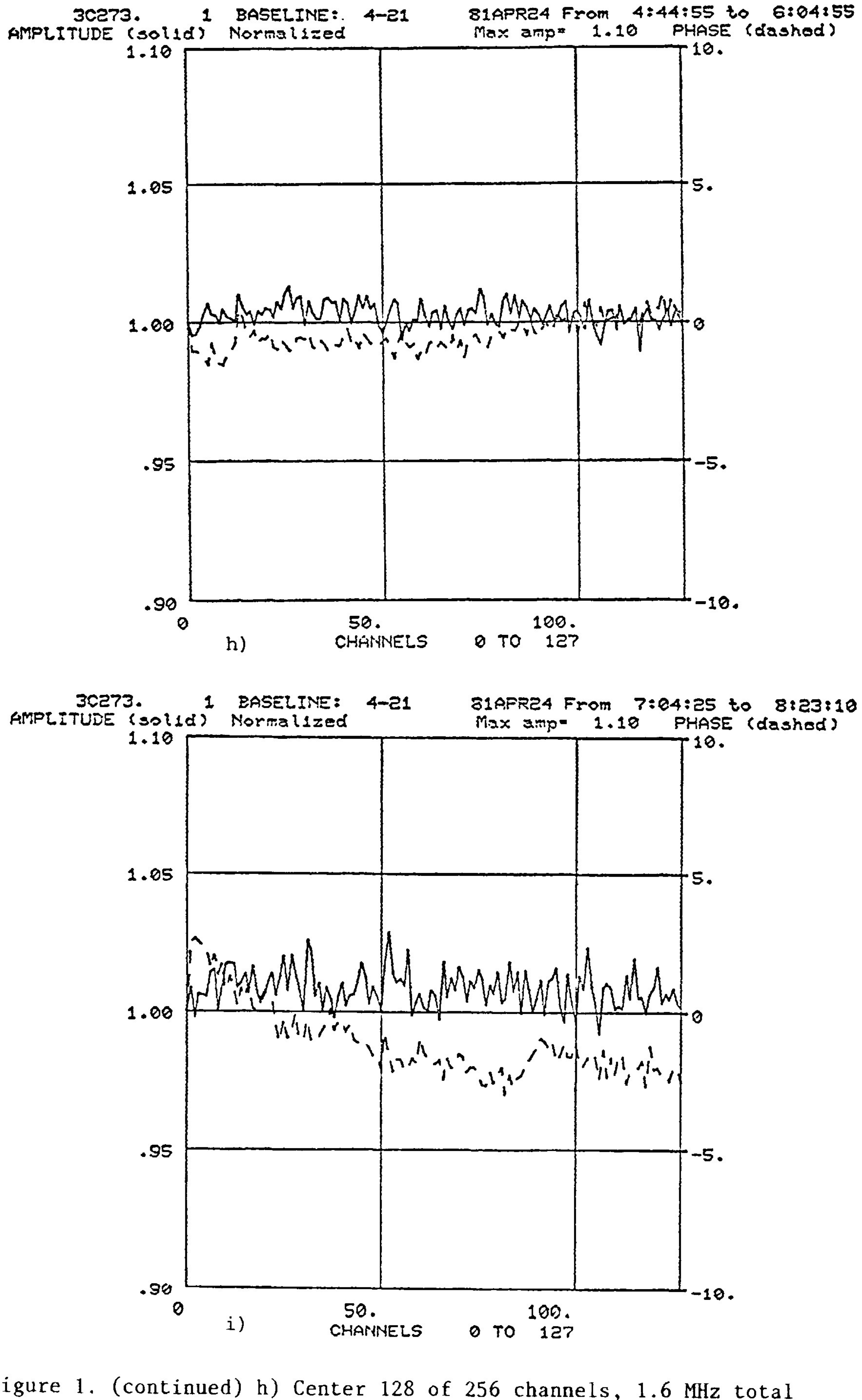

Figure 1. (continued) h) Center 128 of 256 channels, 1.6 MHz total bandwidth, 800 KHz shown; i) Center 128 of 256 channels, 800 kHz bandwidth, 400 KHz shown.

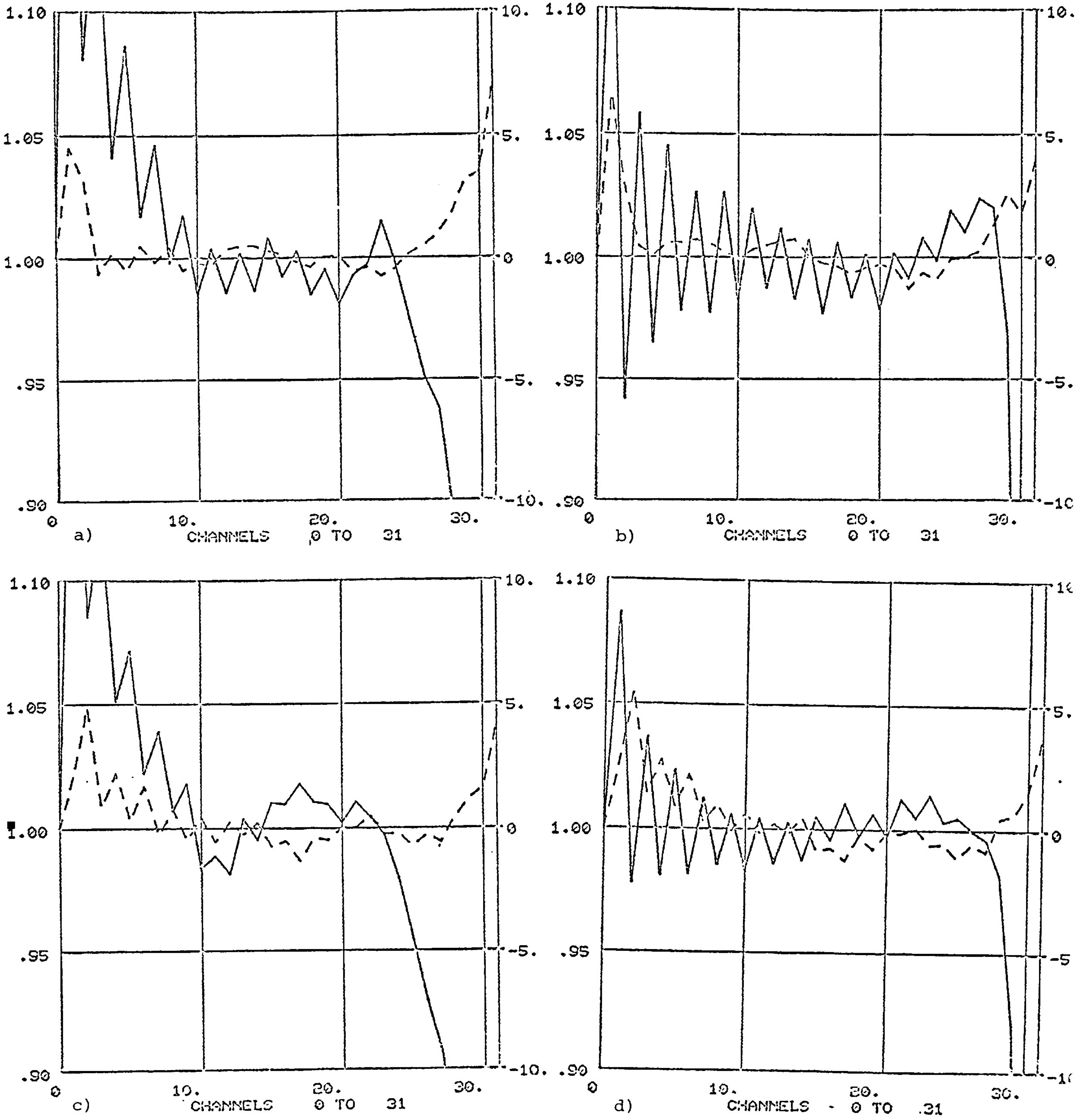

Figure 2. Illustrations of ringing enhanced by normalization. 3C273, 32 channels, 12.5 MHz bandwidth. a), c) and e) unnormalized, b), d) and f) normalized. a) and b) baseline 4-16. c) and d) baseline 4-21 e) and f) baseline 11-15.

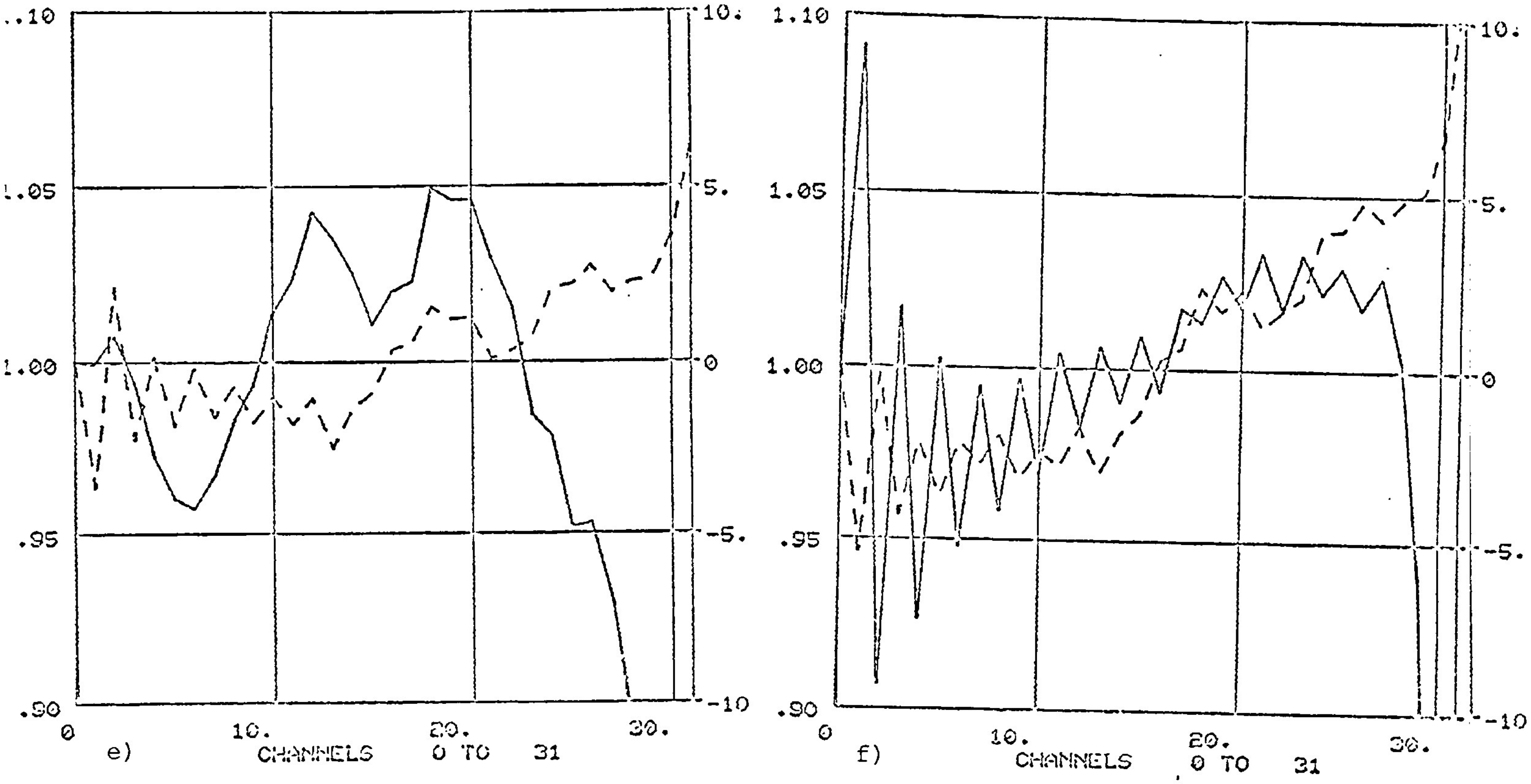

Figure 2 (continued).

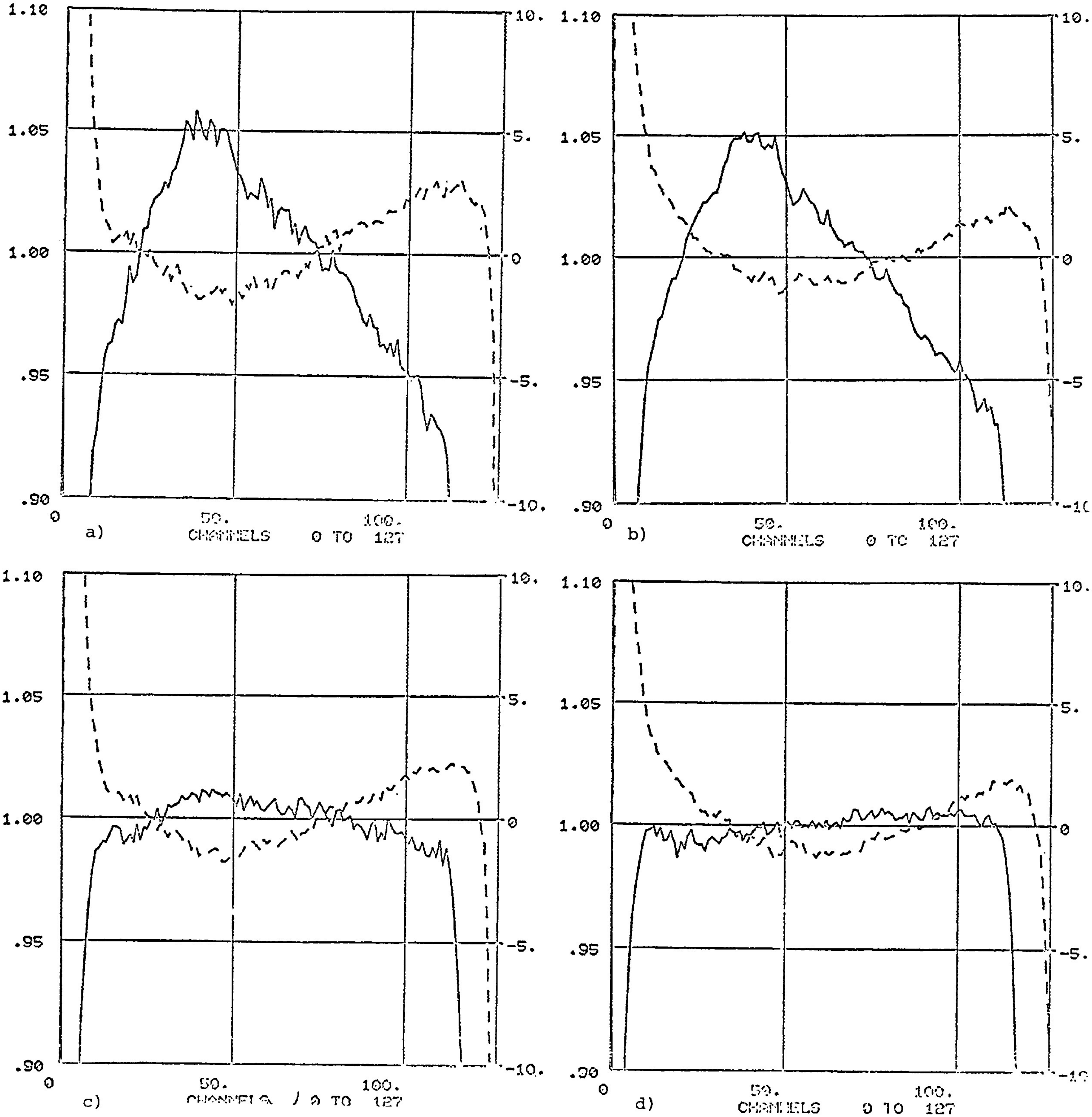

Figure 3. Illustrations of bandpass changes. 3C273, 128 channels, 3.1 MHz bandwidth, baseline 11-16. a) and b) unnormalized, c) and d) normalized. UT times (all on April 17): a) 2:00, b) 5:07, c) 3:33 and d) 7:00.

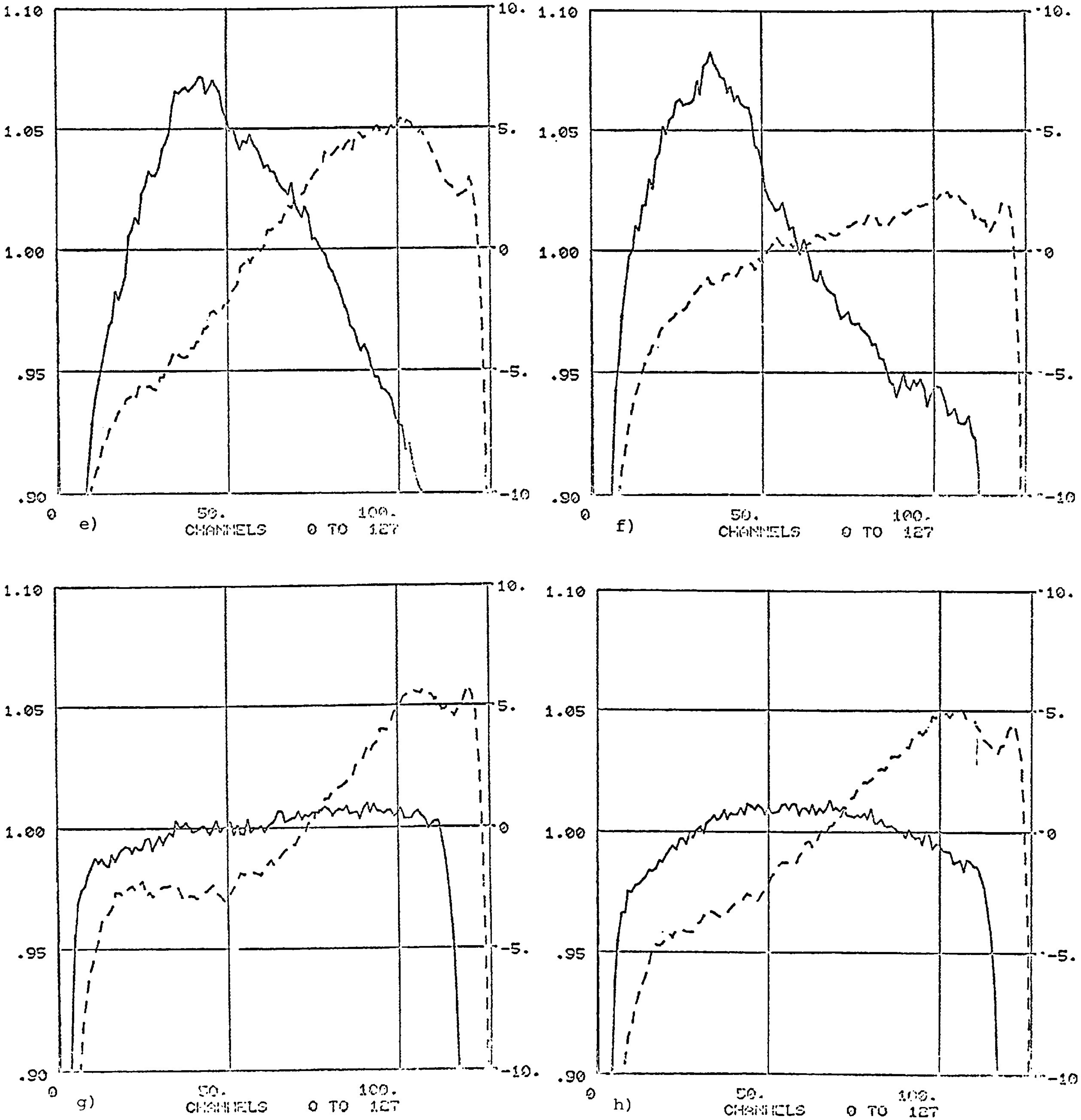

Figure 3 (continued) Baseline 11-28. a) and f) unnormalized, g) and h) normalized. UT times (all on April 17): a) 2:00, b) 5:07, c) 3:33 and d) 7:00.

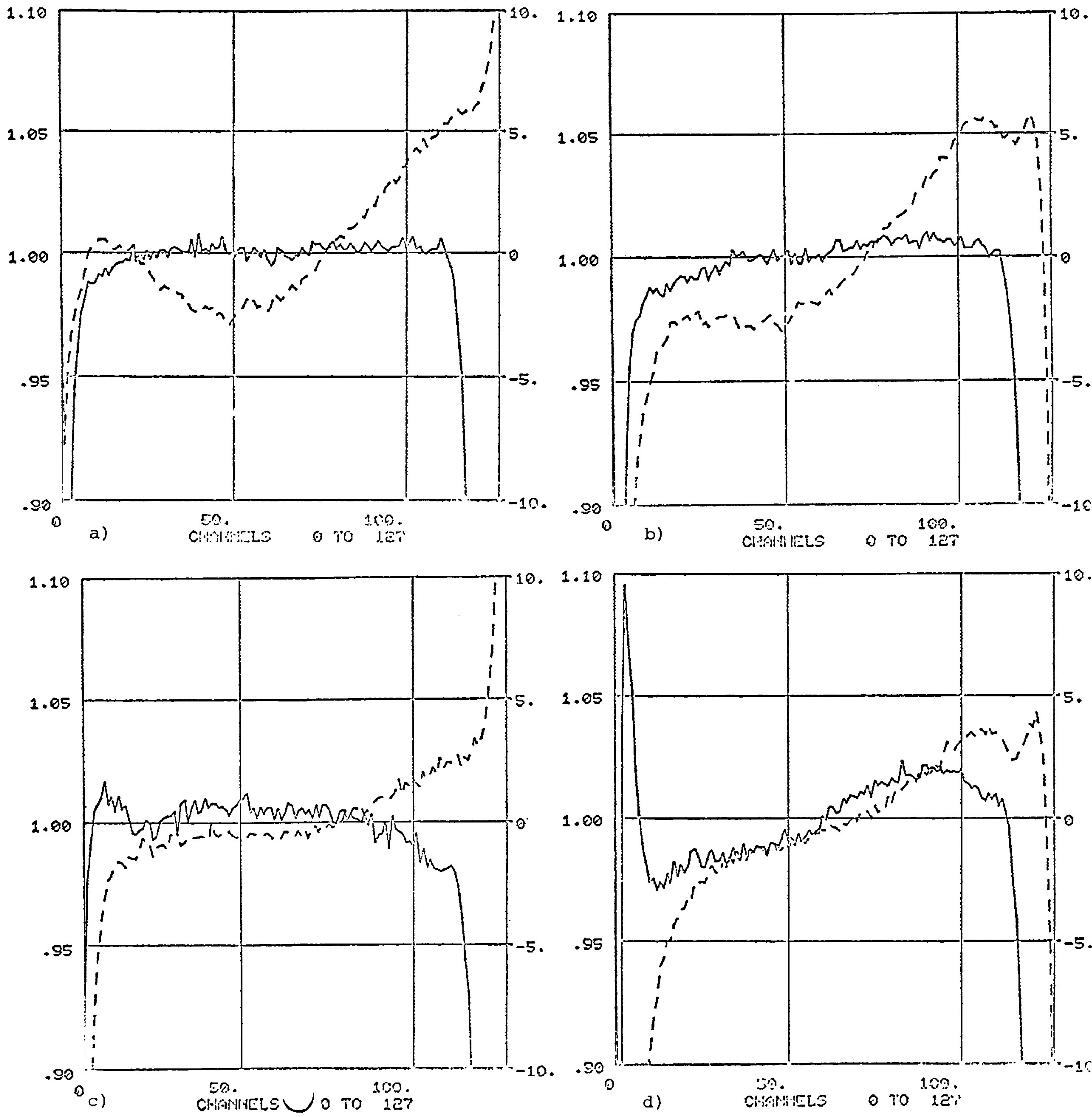

Figure 4. An amplitude closure error. 3C273, 128 channels, 3.1 MHz bandwidth, April 17 at 2:33 UT, normalized. Baselines: a) 11-24, b) 11-28, c) 16-24 and d) 16-28.

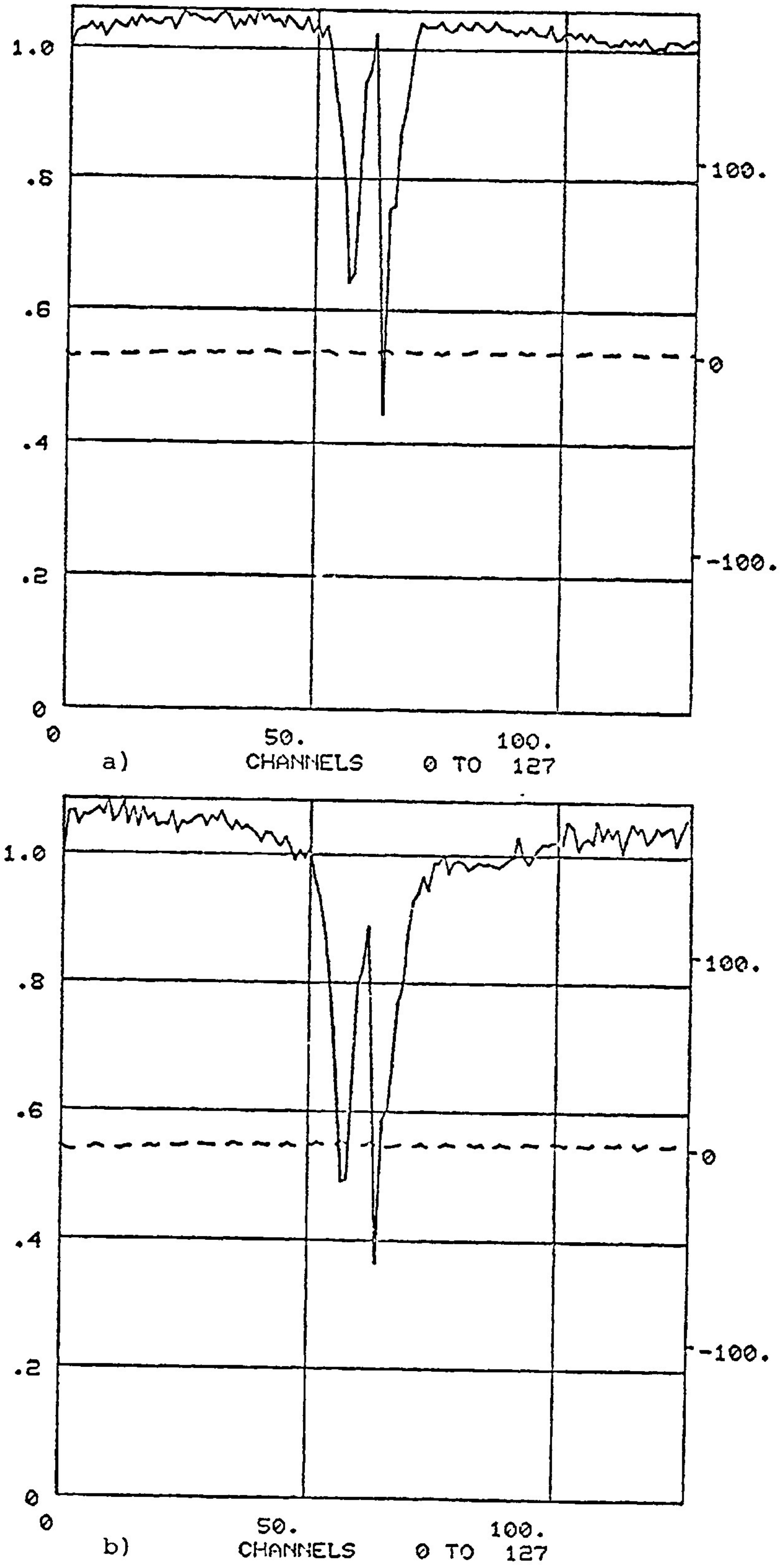

Figure 5. Hydrogen line absorption in 3C147. Center 128 of 256 channels, 1.6 MHz bandwidth (800 KHz shown). Baseline 11-15. a) unnormalized, b) normalized. Note the broad, weak features in b) in channels 40-50 and 70-100, and the greater depth of the lines.