Boundary Layer Receptivity to Weak Freestream Turbulence

Notes on Figures Presented at End-Stage Transition Workshop

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Prepared August 15, 1993; revised September 15, 1993
Work sponsored by NASA

Fig. 1 shows the experimental configuration. The tunnel is about 8 ft long by 2 ft square. In most cases the wind speed is set to 11.6 m/s. Three different plates are used. Each is a quarter-inch thick, extends wall-to-wall, and has a semi-elliptical leading edge. The two extremes in bluntness are shown, being half a 14:1 ellipse and half a 5:1 ellipse. The plate surface pressure is uniform to better than 0.01q, except near the leading edge, or whenever a condition of lift is intentionally applied to the plate. Turbulence is created in the setting chamber by means of eight 1/16-inch hypodermic tubes stretched normal to the flow and pressurized at any controlled value up to 6 psi.. Each has twenty-one 0.006-inch holes spaced at 1-inch intervals along its mid-section of length, and directed upwind. The tubes are spaced vertically at 1.25-inch intervals. The turbulence so created is carried to the test section, where it is found to be spatially uniform over a suitably large cross-sectional area and axial length. ***Fig. 2*** presents spectra of the stream turbulence in the empty tunnel for jet-array pressures of 1 psi to 6 psi. The T-S range extends between 80 and 150 Hz, approximately, for the present conditions. The primary method of fluctuation measurement is by use of microphones installed on the reverse side of the plate. A description of the method and its advantages has been given in AIAA 90-1504. Mean and fluctuating flow measurements are also made by means of various hot-wire probes and rakes carried on a computer-controlled x-y-z traverse mechanism. ***Fig. 3*** shows the layout of a four-foot plate carrying 64 microphones, the outputs of which are digitized simultaneously. The location of a single driver used for creating controlled T-S packets is also indicated.

The boundary layer responds to the turbulence in three (seemingly) distinct ways. First, in examining the broadband u'-fluctuation profile across the layer at some station (given in terms of R, the square-root of the x-Reynolds number) where T-S waves have not yet grown to prominence, one finds that the most obvious motion is what is referred to as Klebanoff's mode (not to be confused with his peak-valley breakdown mechanism) because he first described it in 1970 or 1971. ***Fig. 4*** shows this motion, together with that variation which would result from a thickening/thinning motion of the layer, a similitude pointed out by him. The vertical placement of the curve is arbitrary. Some general characteristics of this mode are:

(1) Long, narrow, high amplitude.

(2) $u'/Uo \propto x^{0.5}$, approx.; downstream, the peak typically exceeds five percent rms.

(3) The distribution in η is as for thickening /thinning of the layer.

(4) The lateral scale is established by the turbulence scale and is $\cong 2\delta$.

The statement as to the narrowness of the disturbances follows from lateral correlation measurements made within the layer and in the stream and shown in ***Fig. 5***.

When one band-limits the signal and examines only those frequency components expected from stability theory to be most-amplified near a particular station, then one finds a second kind of motion, one which is far weaker than the first, as in ***Fig. 6***. A single peak occurs near the outer edge of the layer for the more-forward stations. Note, however, that at the two more-downwind stations the T-S eigenmode has begun to appear near the wall. Therefore, this motion does not resemble the T-S eigenmode, even though the temporal frequencies are similar. Some characteristics of this mode are:

(1) Possesses the frequency of the T-S mode.

(2) Propagation speed = *Uo;* hence λ differs from T-S.

Results on the packet rms amplitude under a variation in the stream turbulence level are given in *Fig. 12*. The results pertain to a specific frequency within the unstable portion of the TS band. The ordinate is the wall pressure fluctuation component due to TS waves at a particular frequency, shown with arbitrary scale. The abscissa is the component of the freestream turbulence at the *same frequency* as the turbulence level was raised. Each curve corresponds to a particular axial station. The minimum critical R for the parallel-flow boundary layer is near 300. Thus, it is possible to detect TS components at stations as far forward as that point, but it must be pointed out that packets, if present there, could not be distinguished by eye amid the total signal. Isolation of the TS component at the forward stations therefore relied upon the technique of measuring the spectrum with turbulence present and then subtracting the spectrum measured with no added turbulence. The figure shows that the response to turbulence was linear at the forwardmost station, but that it became increasingly nonlinear with increase of x. Further evidence of the nonlinear response to turbulence is given in *Fig. 13*. There, the average amplitude of the passing packets, detected individually through analysis of the time- series records, is presented as a function of R for four levels of turbulence. It appears that a rapid rise in amplitude commenced well downstream of the minimum critical Reynolds number, corresponding to the formation of packets.

Recent studies have made use of the 64-microphone array, together with simultaneous hot-wire measurements. *Fig . 14* summarizes some results. It can be seen in the left frame that packets forced by means of the driver indicated in Fig. 3 are much wider than those induced by turbulence. The lateral variation in peak strength is shown for five turbulence-induced packets passing the station R = 831 at various times. These have been selected from the great number recorded such as to be approximately similar in strength to the forced ones. Clearly, the ones due to turbulence are narrow. The right side shows that turbulence- induced packets are sometimes much stronger than the strongest ones which can be forced without serious waveform distortion due to incipient breakdown. Also seen there is an intercomparison of microphone and hot-wire signals.

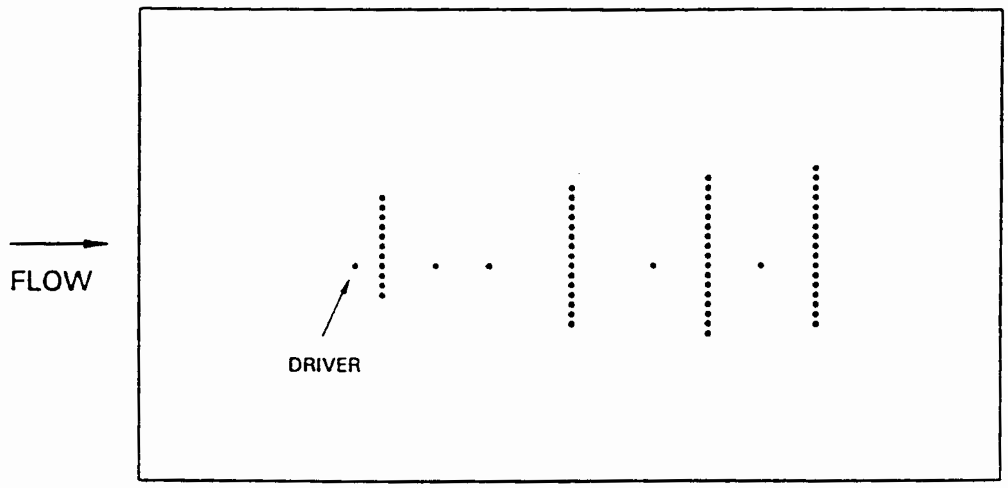
Fig. 15 gives time traces for several microphones and for a five-wire vertical rake. Two large, and several small, packets are seen in the microphone traces. The effect of the largest is also to be seen in one of the hot-wire records. The hot wires also reaffirm in a general way the presence of T-S-range frequencies in the outer layer, as well as a predominance of low frequencies in the inner layer. Five instants of time have been selected to display the instantaneous profiles given in *Fig. 16*. Substantial distortion is apparent.

Figs. 17 and *18* show the time history of repetitively forced packets. The results are presented in the form of 60 time traces, with each "box" corresponding to a microphone shown in Fig. 3 (the layout here is inverted top-to-bottom, and no traces are included for the four centerline sensors not part of a lateral array.) Fig. 17 is for a quiescent stream, and Fig. 18 is for a weakly turbulent one. The (relative) amplitude range of display differs in the two cases, and is indicated in the figures. The results within the former figure are as expected, but the addition of turbulence has greatly altered the packet development, rendering the packet locally both stronger and locally weaker than in the quiescent case, and has also produced an additional, unsynchronized, packet which has grown to become a burst. *Fig. 19* shows a turbulence-induced packet which breaks down to become a burst.

Some results on the packets can be summarized as follows. The turbulence-induced ones:

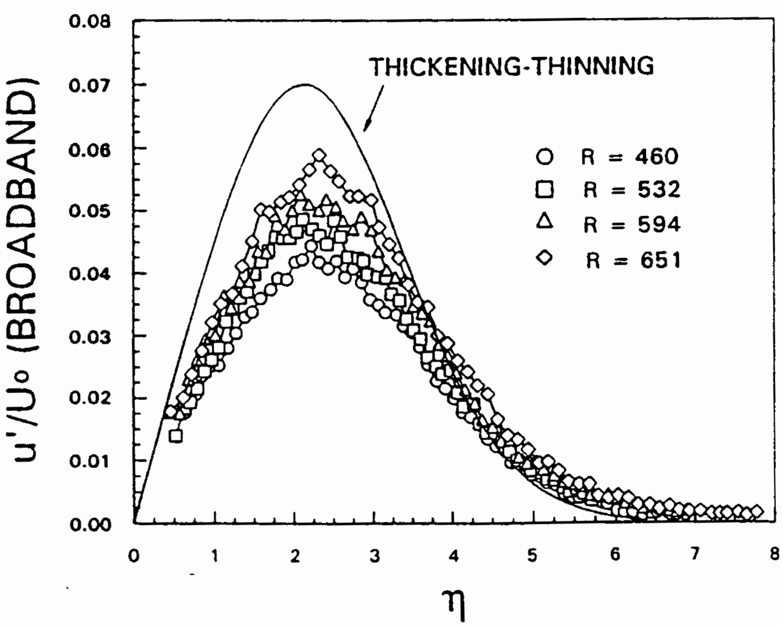
(1) Mainly arise at stations downstream of the min. crit. Reynolds number.
(2) Possess a strength not in linear proportion to the stream turbulence
(3) Travel at the expected speed.
(4) Have slightly higher frequency content than forced ones.
(5) Possess the expected amp. dist. in the near-wall region, but not in the outer region.
(6) Are surprisingly narrow.

MICROPHONE LAYOUT
122-cm PLATE



3.

K - MODE FLUCTUATIONS
DUE TO FREESTREAM TURBULENCE



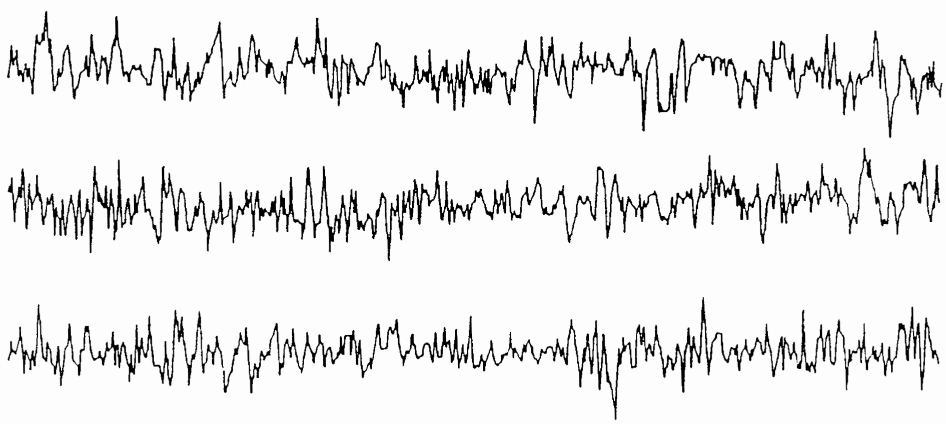
4.

THREE EXAMPLES:

FREESTREAM FLUCTUATION RECORDS

0.65 sec DURATION EACH

u'/Uo = 0.22 %



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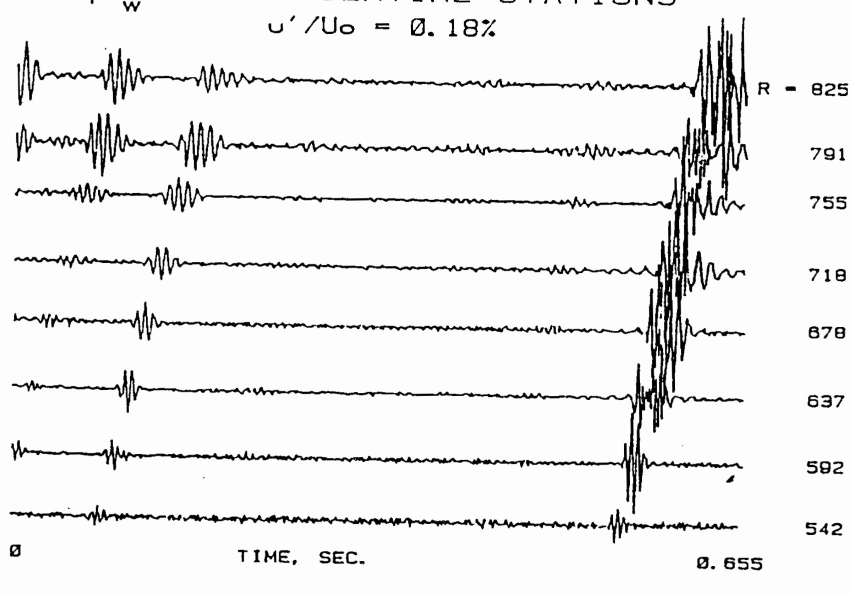
P$'_w$ AT SEQUENTIAL STATIONS

u'/Uo = Ø. 18%



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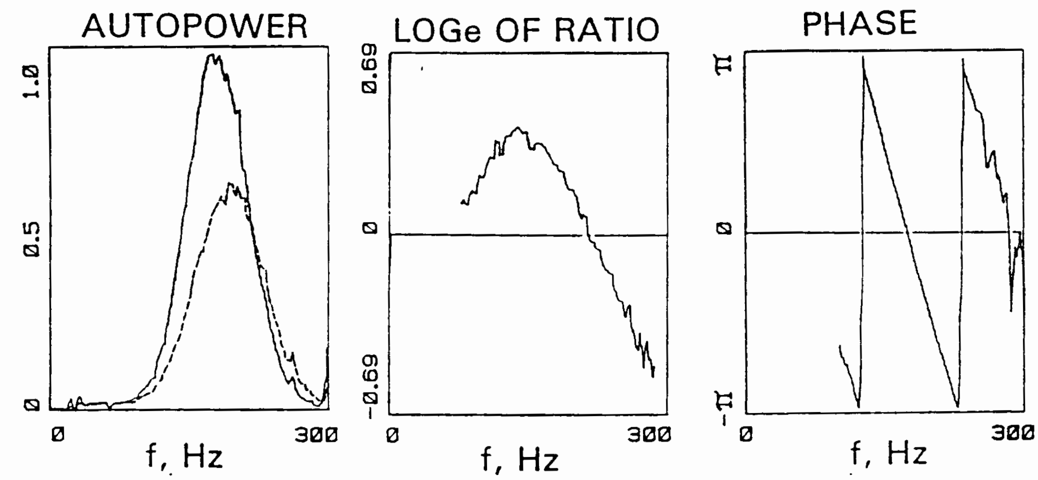
EXAMPLE OF

LONG-AVERAGE POWER SPECTRA

STATIONS R = 494 and 519



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IN COMPARISON WITH STABILITY THEORY RESULTS,
FST-INDUCED PACKETS POSSESS SIMILAR:

* Propagation Speed
* Frequency Content
* Growth Rate
* Amplitude Distribution thru Layer

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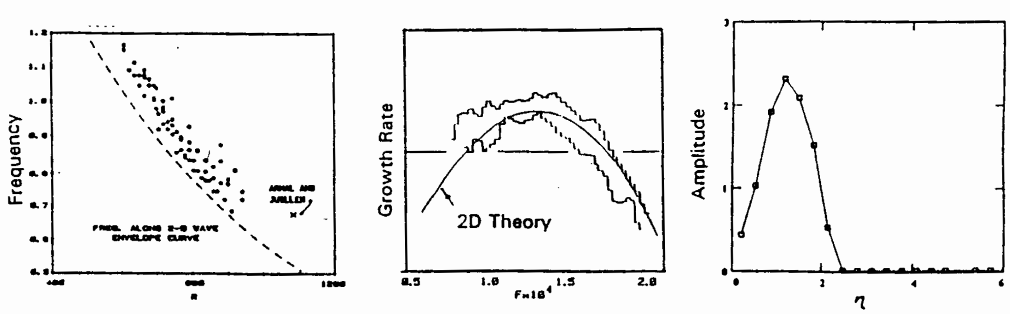
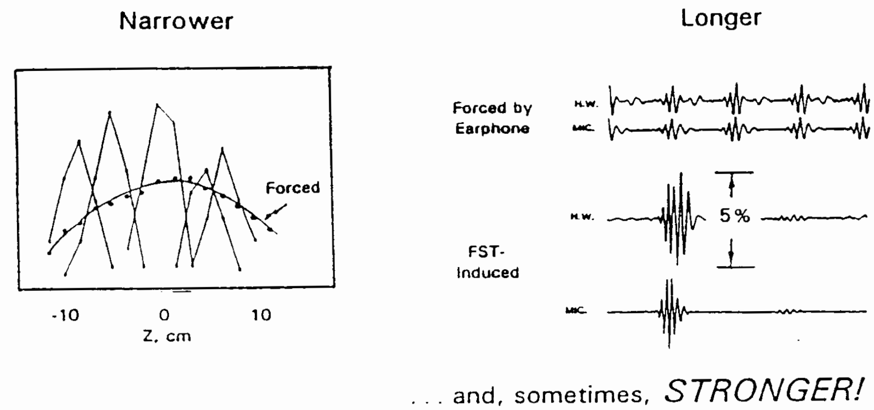


Comparing to Gaster Packets, FST-Induced Ones Are:



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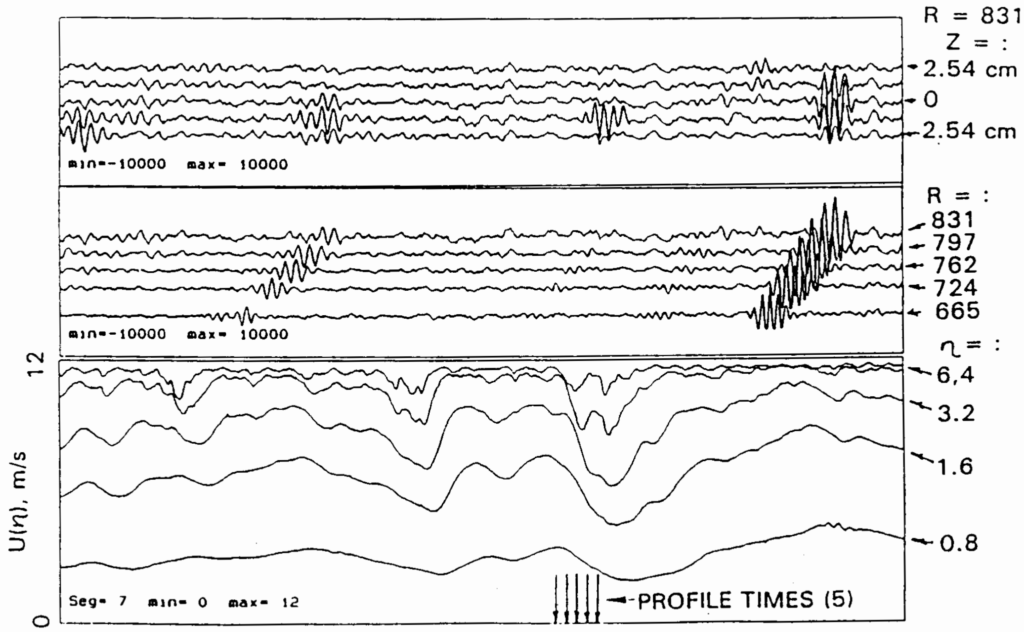
SIMULTANEOUS RECORDS: MICROPHONES AND HOT-WIRE RAKE

FST LEVEL: u'/Uo 0.2 %   0.65 SEC. OF DATA



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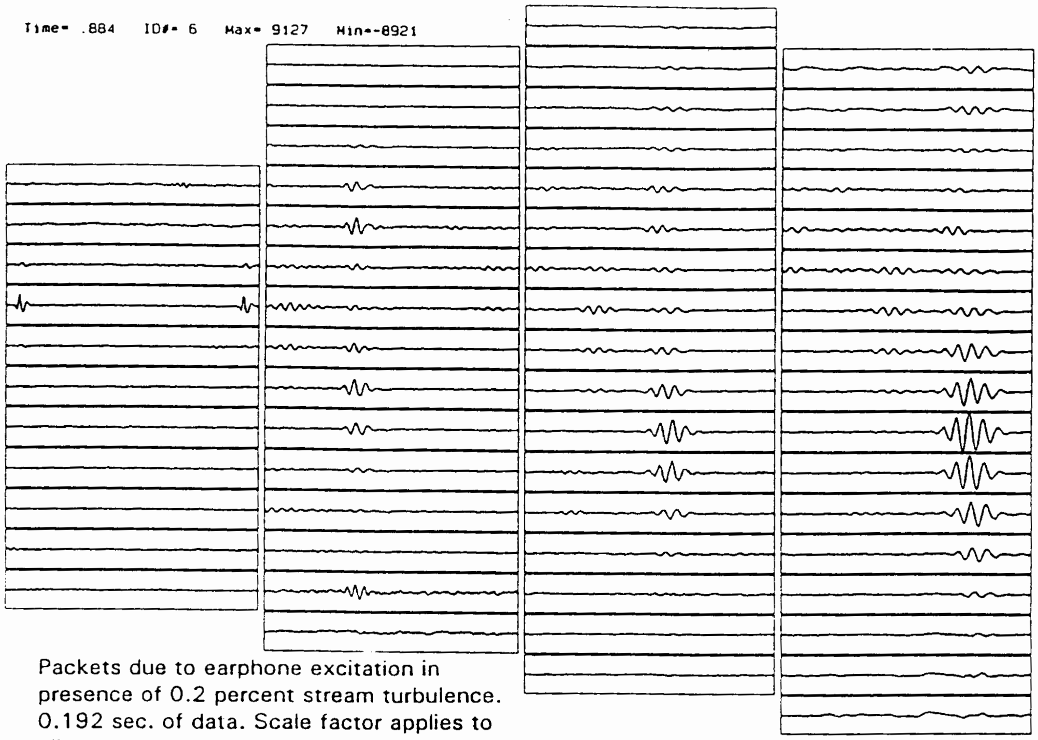
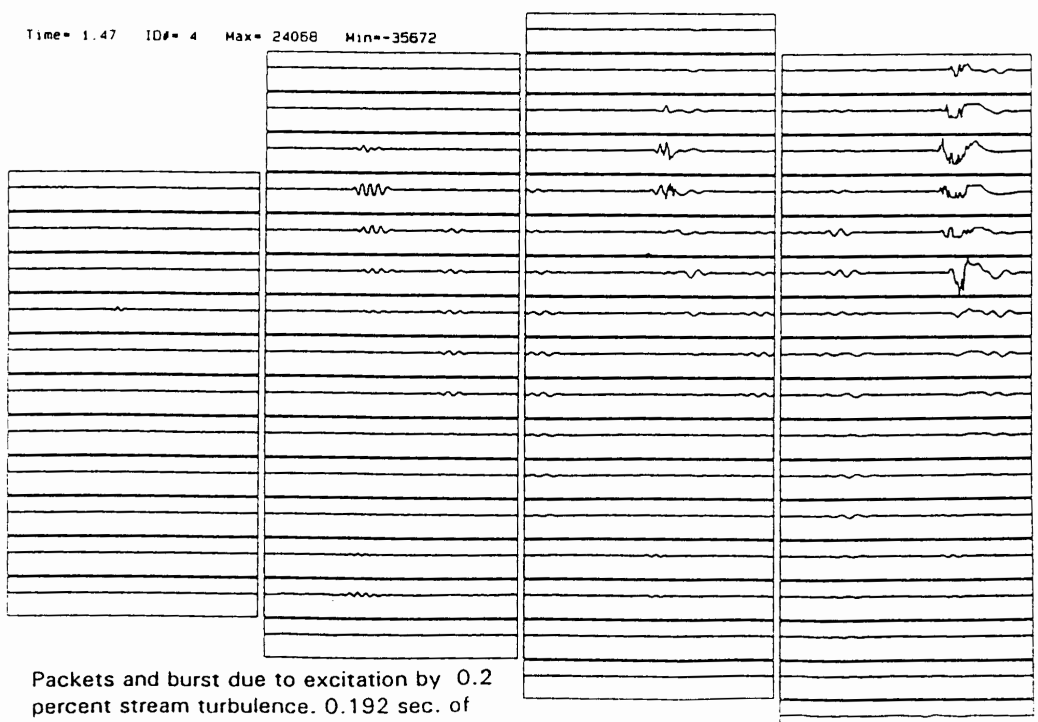


Packets due to earphone excitation in presence of 0.2 percent stream turbulence. 0.192 sec. of data. Scale factor applies to all traces.

18.



Packets and burst due to excitation by 0.2 percent stream turbulence. 0.192 sec. of data. Scale factor applies to all traces.

19.