4th Intl. Reflectometry Wksp. for Fusion Plasma Diagnostics. Cadarache, March 22nd -

FR0002667

Phase ramping and modulation of reflectometer signals

G.D.Conway, D.V.Bartlett, P.E.Stott

JET Joint Undertaking, Abingdon, Oxon, U.K.

Abstract

The phase and amplitude signals of JET heterodyne reflectometers show varying levels of high frequency turbulence superimposed on a slow changing mean. The phase signal also shows multi-radian (> 1 fringe) variations with two quite different time scales (2-10 ms and sub-ms). In both cases the mean reflected power, together with turbulent phase and amplitude fluctuation levels, are modulated synchronously with the phase fringes. The slow fringes appear to result from radial movement of the cutoff layer with the amplitude modulation possibly due to multiple reflection between plasma and wall. The fast fringes occur in intermittent bursts and appear to be phase runaway resulting from antenna misalignment. Using a 2D physical optics simulation code it is possible to replicate the fast bursts of phase runaway from steady-state turbulence and misaligned antennas. This offers a possible alternative explanation for some of the observations of bursting turbulence seen in reflectometer signals.

1. Introduction

Typically reflectometer signals, i.e. the relative phase and reflected power or amplitude, show a large level of high frequency fluctuations (turbulence) superimposed on a slowly varying mean. In the case of the JET X-mode heterodyne reflectometers the phase signal also displays multi-radian excursions (fringes) with two distinct time scales. Slow fringes or phase ramps occur at a rate of one per 2-10 ms, while fast multi-fringe ramps are on a sub-millisecond scale. Phase fringes can be generated by one of three mechanisms:

(1) Large scale radial movement of the cutoff layer due to changes in either the mean density or profile shape (for O or X-mode) and magnetic field ramps (for X-mode only).

(2) A misalignment in the reflectometer antenna geometry relative to the surface normal.

(3) An asymmetry in the shape of the cutoff layer perturbations - such as a sawtooth shaped density perturbation.

The last two cases both require perturbations in the cutoff layer, whether random turbulence or single mode MHD, to be moving transverse to the antenna (i.e. plasma rotation). Both cases can also generate a Doppler shift in the reflected signal leading to the ubiquitous phase ramping, or runaway, that appears in almost all experimental reflectometer signals.

Phase runaway is usually described as a monotonic increase or decrease (drift) in the mean phase with time, usually through tens or hundreds of radians (i.e. multiple fringes) in a matter of milliseconds [1-5]. This degree of phase change cannot be explained by a radial movement of the cutoff layer alone. In this paper we will show that the presence of fringes or phase ramping modulates the measured level of turbulence and hence complicates the interpretation of reflectometer signals, whether for profile reconstruction or for plasma turbulence measurements. Further, using a 2D physical optics simulation code [6] it will be shown that it is possible to replicate the fast bursts of phase runaway from purely steady-state turbulence and misaligned antennas.

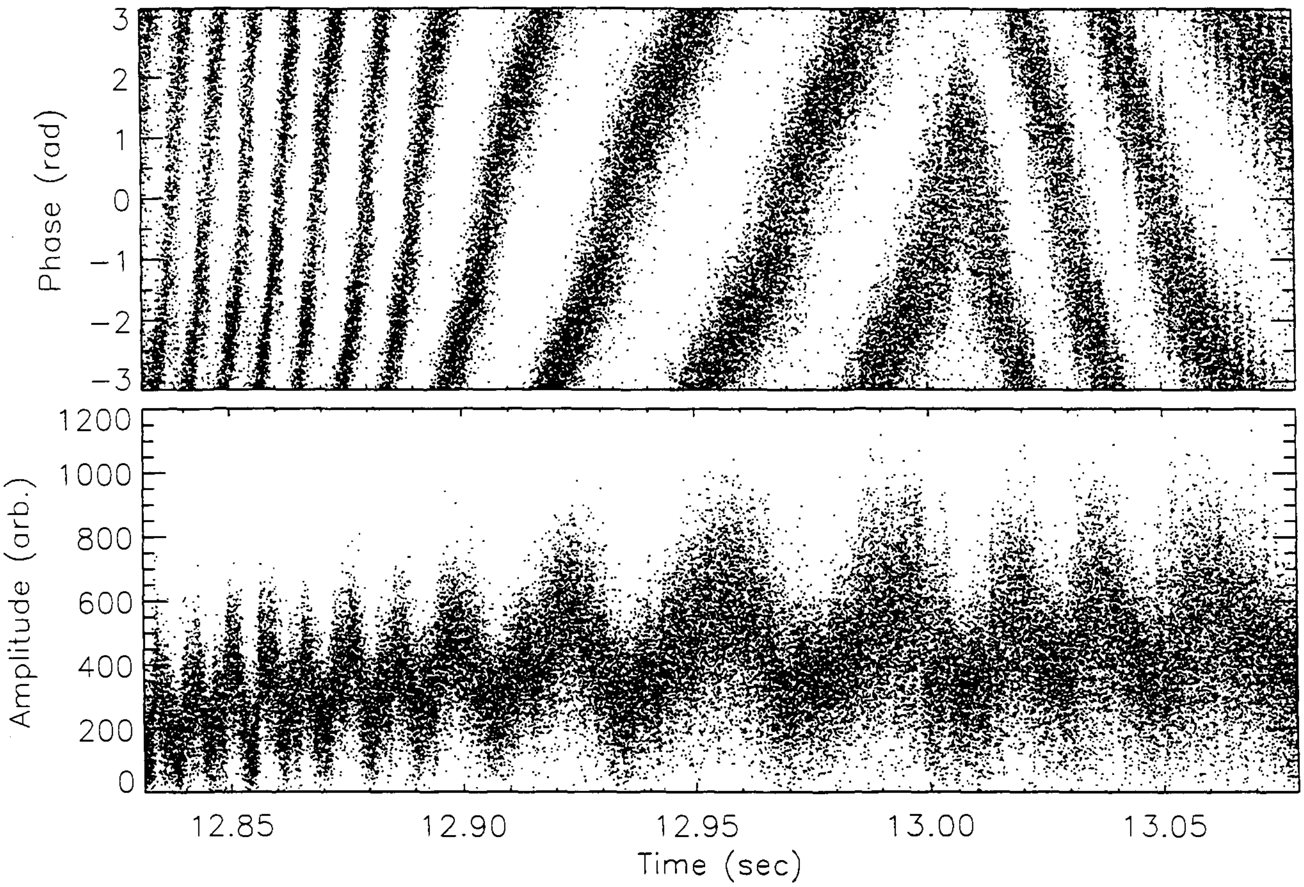


Figure 1: 250 ms long time traces of raw phase and amplitude signals from a 105 GHz X-mode reflectometer ($r/a \approx 0.8$) *during JET shot #40477. Sample period is 4 μs.*

2. Experimental data - slow fringes

Fig. 1 shows a 250 ms long time sequence of the raw phase ϕ (modulo 2π radian) and amplitude A signals from a 105 GHz X-mode reflectometer [7] during an ELM-free period of a JET Hot ion H-mode plasma (shot #40477). The phase clearly moves through several fringes, at an initial rate of about 120 Hz, but gradually slows down, then reverses direction for about 6 to 7 ms, and then (not shown in figure) it becomes stationary. The amplitude signal also shows a corresponding modulation in its mean value synchronised with each phase fringe, and, that the phase ramp is not linear - it has a distinct 's' shape. These phase and amplitude variations are consistent with the behaviour predicted by 2D simulation codes [4-6] for a rotating MHD mode and misaligned antennas - i.e. phase runaway. A closer inspection of Fig. 1 reveals that the level of turbulent fluctuations in the phase and amplitude are also modulated synchronously with the fringes - this is particularly evident in the amplitude fluctuations. Fig. 2 shows a contour plot of the Fourier spectrum of the phase fluctuations as a function of time. There appears to be bursts of broadband turbulence. Indeed this data was originally interpreted as evidence of bursting turbulence associated with thresholds [8]. However it is suspicious that the bursts occur at the same point in each phase fringe. The spectrum of Fig. 2 also shows a 20 kHz mode running through the whole time window. Mirnov coil (magnetic) signals indicate that this is an $n = 2$ mode, which is consistent with the toroidal rotation frequency of approximately 60 $\mathrm{krad\,s^{-1}}$ at the cutoff layer location (plasma edge / separatrix region $R \approx 3.8$ m) measured by

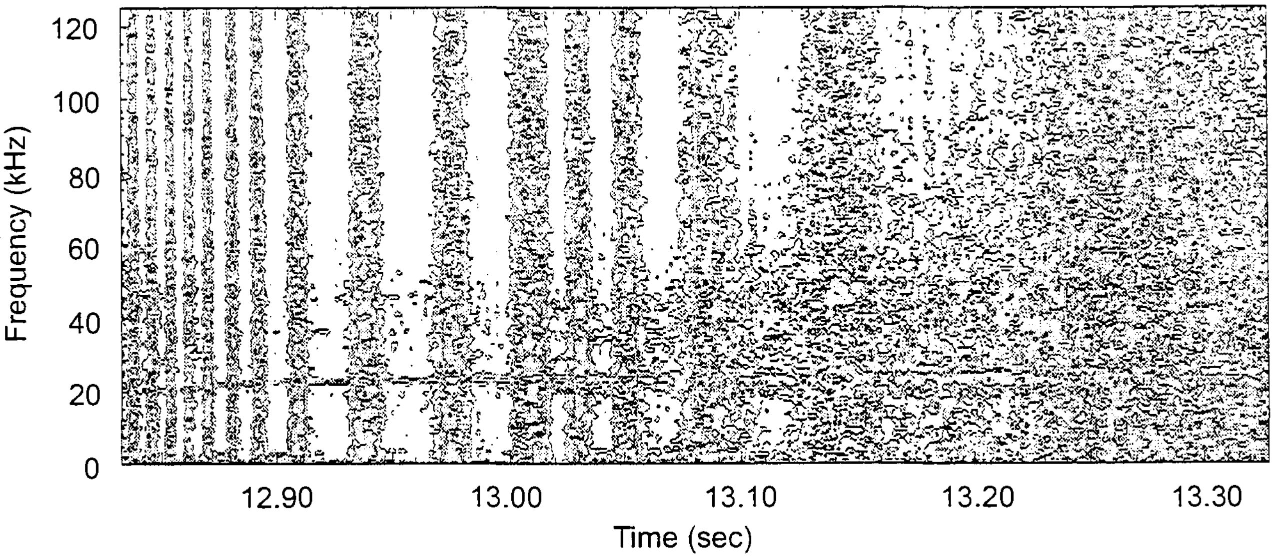
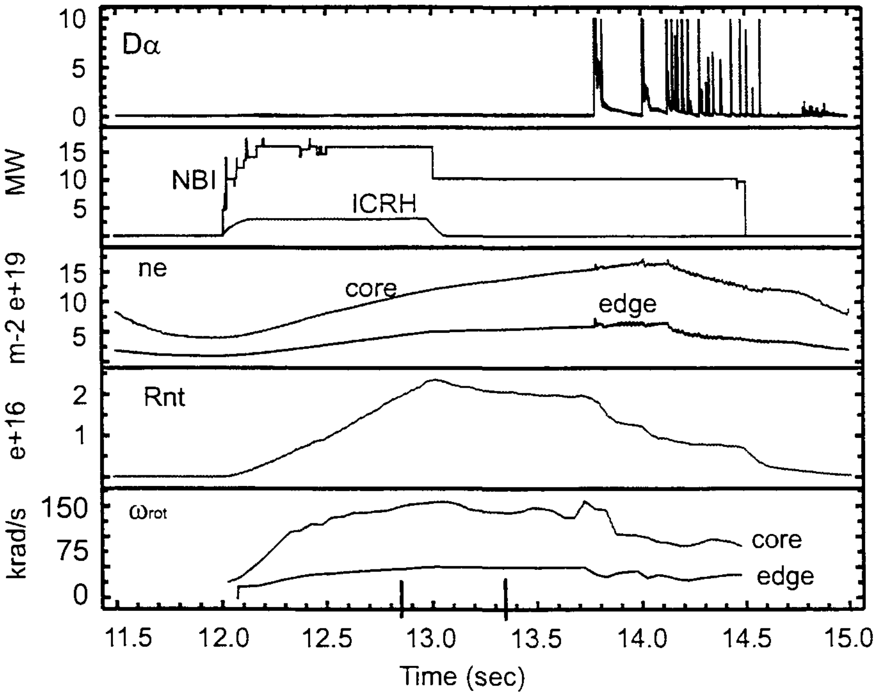


Figure 2: Contour plot of log spectral intensity (frequency vs time) of phase fluctuations signals shown in Fig.1 (shot #40477). Note coherent mode at 20 kHz.

charge exchange spectroscopy, shown in the plasma parameter time traces of Fig. 3. Unfortunately such a fast rotation frequency is inconsistent with the fringe rate of only 120 Hz, and there is no reversal in the rotation direction! So this appears to rule out phase runaway due to a rotating MHD mode and antenna misalignment. It is possible that an edge locked mode slowing down and then locking to the vessel could explain the slow fringes, but there is no evidence of a locked mode in the magnetics.

Figure 3: Plasma parameter time traces for ELM-free Hot-ion H-mode shot #40477.



If the slow fringes are not due to phase runaway then they must result from radial movement of the cutoff layer. In Fig. 3 there is a step down in the neutral beam power at 13.0 seconds which coincides with the reversal in the phase ramp direction. With the step down there is a consequent slowing down in the rate of the core density rise, but unfortunately no clear decrease in edge density.

However it is possible that there may be subtle changes in the density profile not revealed in the course measurements of the interferometer chords. There are however other problems with the simple cutoff layer movement explanation. Neither the 's' shaped phase fringes or the amplitude modulation are expected to appear with a simple radial movement of the cutoff layer. Therefore there must be another 2D or 3D effect present. One possible answer is interference resulting from multiple reflection of the microwave beam between the cutoff layer and the antenna/vacuum vessel [9]. For shot #40477 the cutoff layer is close enough to the plasma edge for this to occur.

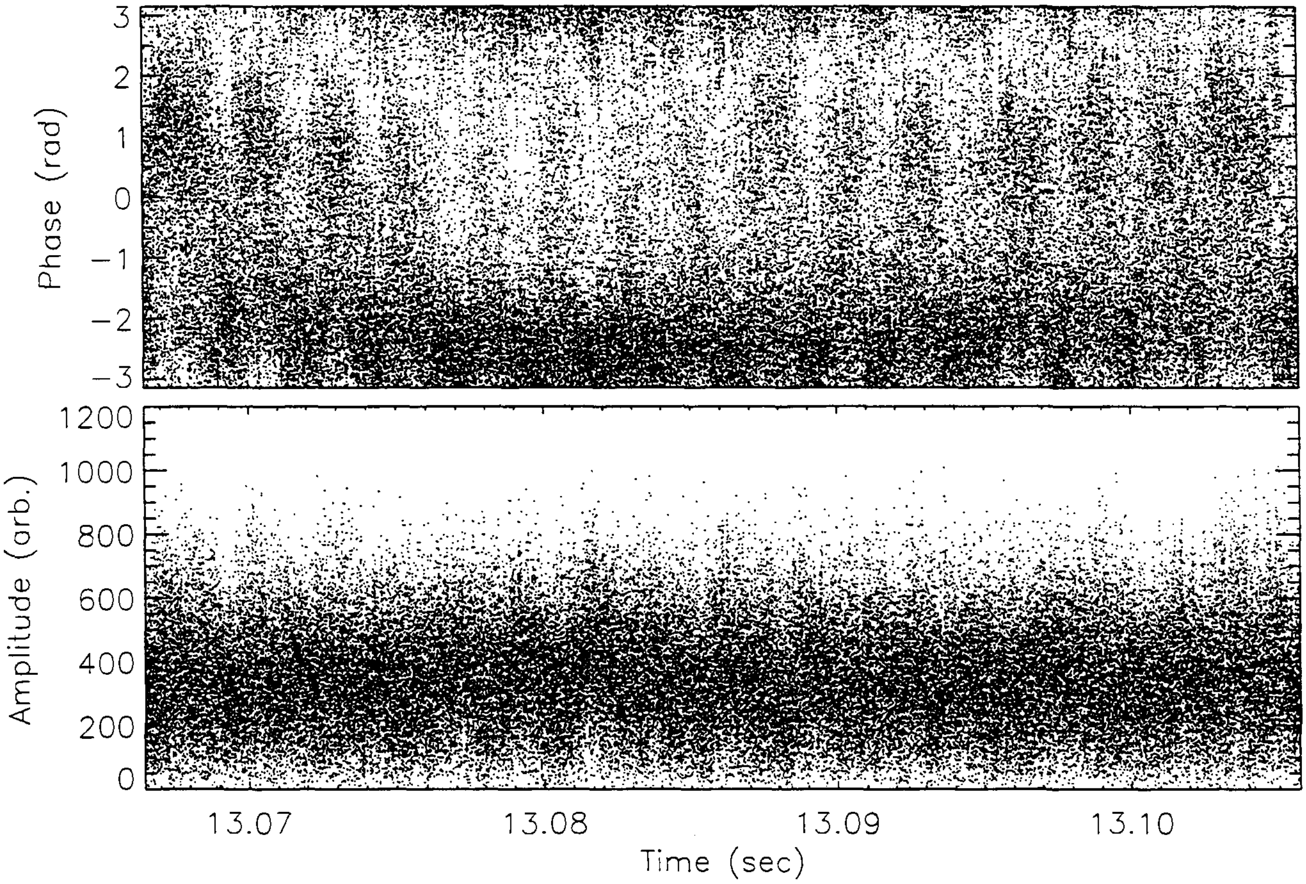


Figure 4: Expanded time sequence of phase and amplitude signals from shot #40477 using a 0.5 μs sample period.

3. Experimental data - fast fringes

At the end of the time traces in Fig. 1 there appears to be some fine-scale temporal structure to the phase and amplitude turbulence. Expanding this section in Fig. 4 (0.5μs sample period) shows that the fine-structure is actually bursts of multiple fringe ramps with a sub-millisecond time scale. Compared to the slow fringes these fast bursts of phase ramping are more consistent with phase runaway due to misalignment/asymmetry and also appear to be the same bursting phenomena reported in [2,4].

The fast phase ramping is present throughout the whole of the Fig. 1 time window but it most clear after the NBI power step down when the phase has no slowly varying mean component. These "micro-bursts" of phase runaway are an exceedingly common feature in JET reflectometer signals. Fig. 5 shows another example from the plasma core region during the ohmic phase of an optimized shear discharge (shot #46270) using a 75 GHz reflectometer (1μs sample period). Again the amplitude signal (reflected power) is seen to fall during the bursts.

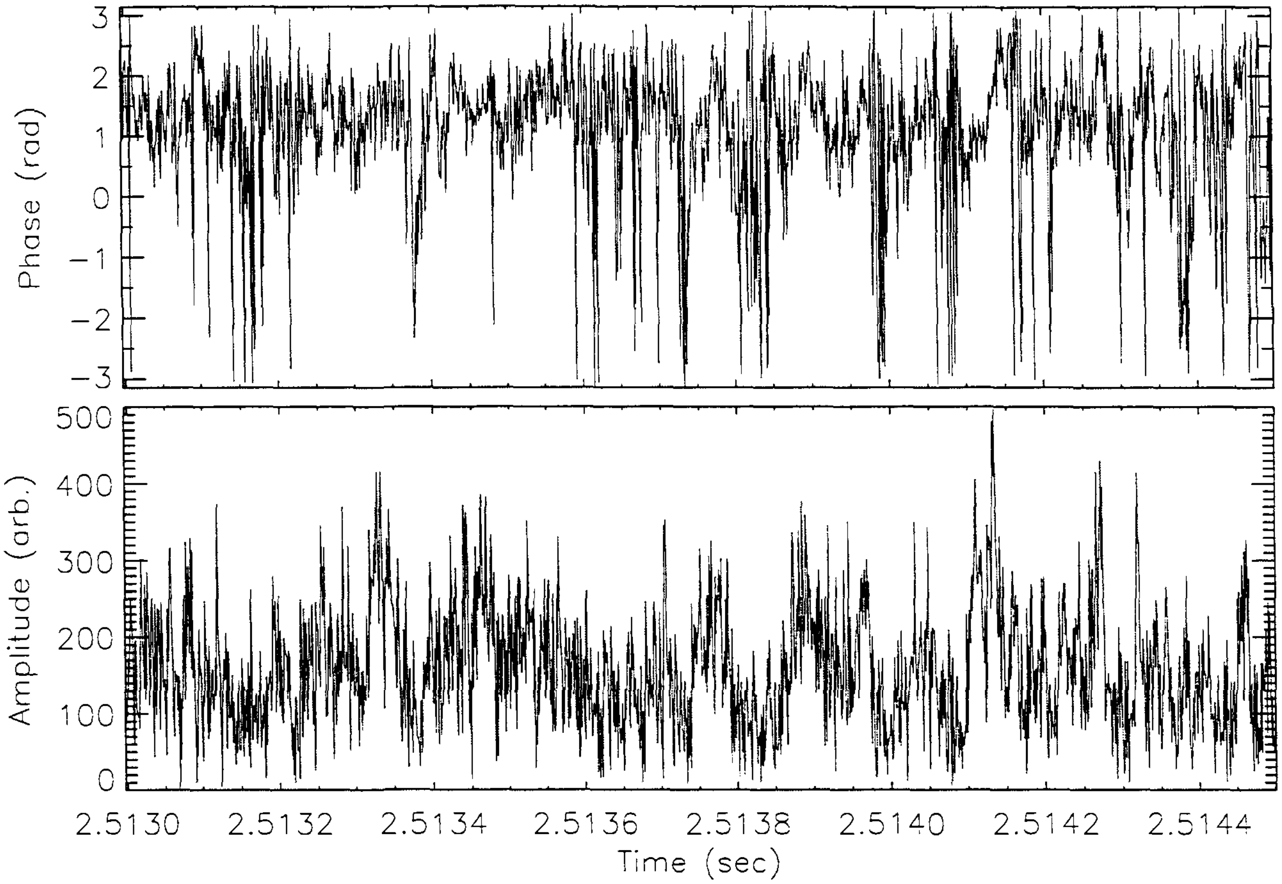


Figure 5: Raw phase and amplitude signals from the JET plasma core during the ohmic phase of an optimized shear discharge (shot #46270) using a 75 GHz X-mode reflectometer. $1\mu s$ sample period.

Fig. 6 shows the corresponding Fourier spectra for the phase ϕ and amplitude A signals (single sided) together with the phase-amplitude γ^2 coherence, cross-phase spectra, distributions (pdf) of ϕ and A, and the double-sided spectrum of the complex amplitude $A\exp(i\phi)$ signal. The complex amplitude spectrum shows a clear Doppler shift and the cross-phase spectrum the characteristic quadrature $\pm\pi/2$ phase shift at the coherence peak. Note the phase pdf is distinctly non-Gaussian. Also note that the mean phase in Fig. 5 always returns to the same value after each fringe ramp / micro-burst. This is to be expected if the phase ramp is due to a Doppler shift resulting from misalignment/asymmetry since 2D simulations show that the phase always moves through multiples of 2π (i.e. a fringe) for each period of the mode [6]. Hence ϕ will always return to it's pre-runaway value and the mean phase remains constant. On the other hand, for a simple random radial movement of the cutoff layer there is no reason to expect the phase to stop at the same point in the fringe cycle.

4. Simulation results

One explanation for bursting turbulence - which from the experimental evidence is clearly associated with bursts of phase ramping - suggests that there are competing terms driving and suppressing the underlying plasma turbulence [2]. However, using a 2D physical optics simulation code [6] with transverse propagating broadband Gaussian turbulence and a small antenna misalignment it is possible to obtain a non-stationary Doppler shift ($f_D = d\phi/dt$) over a wide range of simulation parameters.

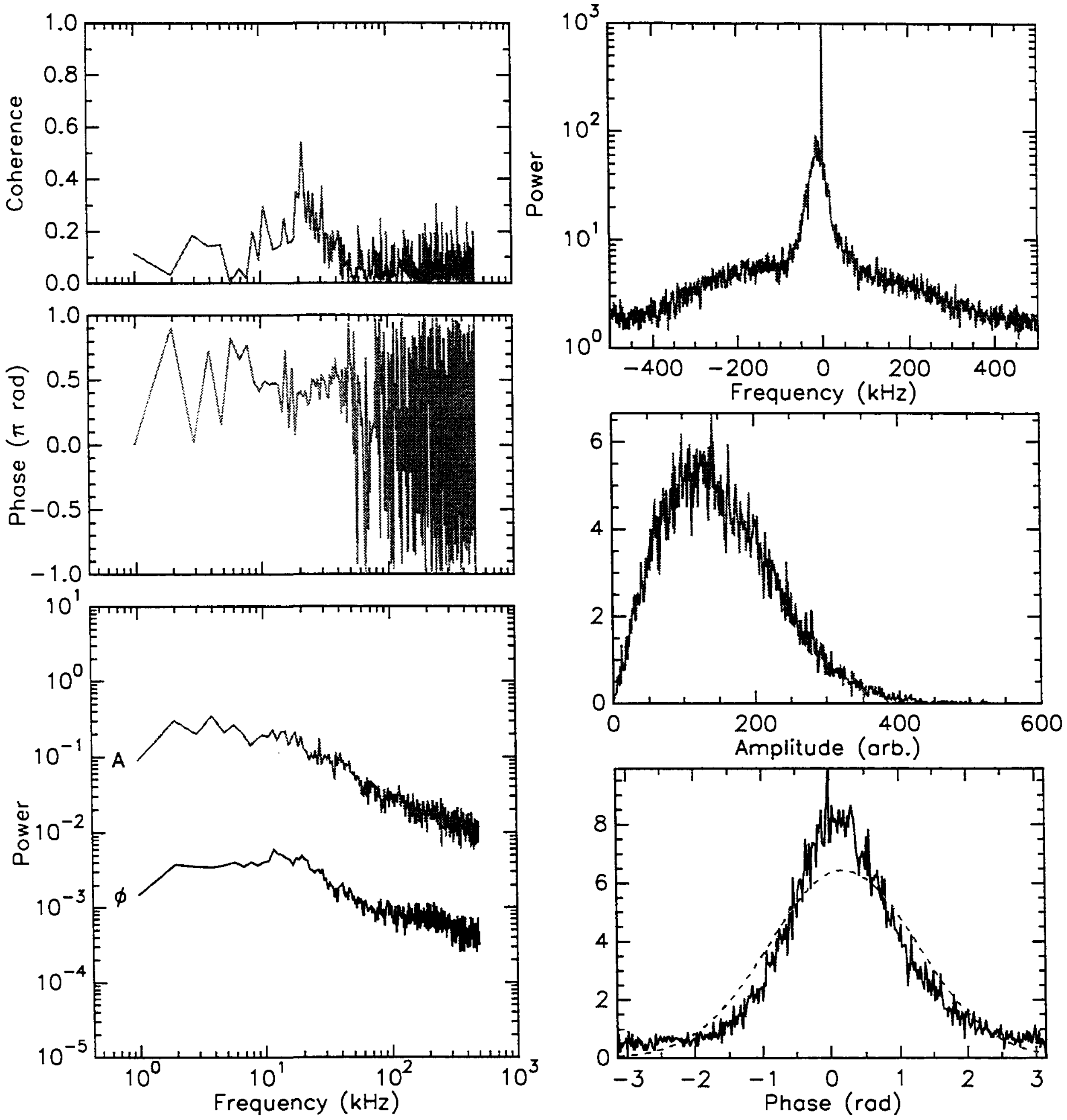


Figure 6: Fourier, coherence and cross-phase spectra, with phase and amplitude pdf, and double-sided complex amplitude spectra of experimental signals shown in Fig. 5.

This varying Doppler shift means that the phase ramping is not uniform but occurs in steps. Sometimes the steps are as few as 2 or 3 fringes, or several tens of fringes inter-spaced by no phase runaway. This behaviour is most pronounced if an MHD type mode (i.e. dominant single frequency) is added to the broadband random fluctuations - such as in the experimental case of Fig. 2.

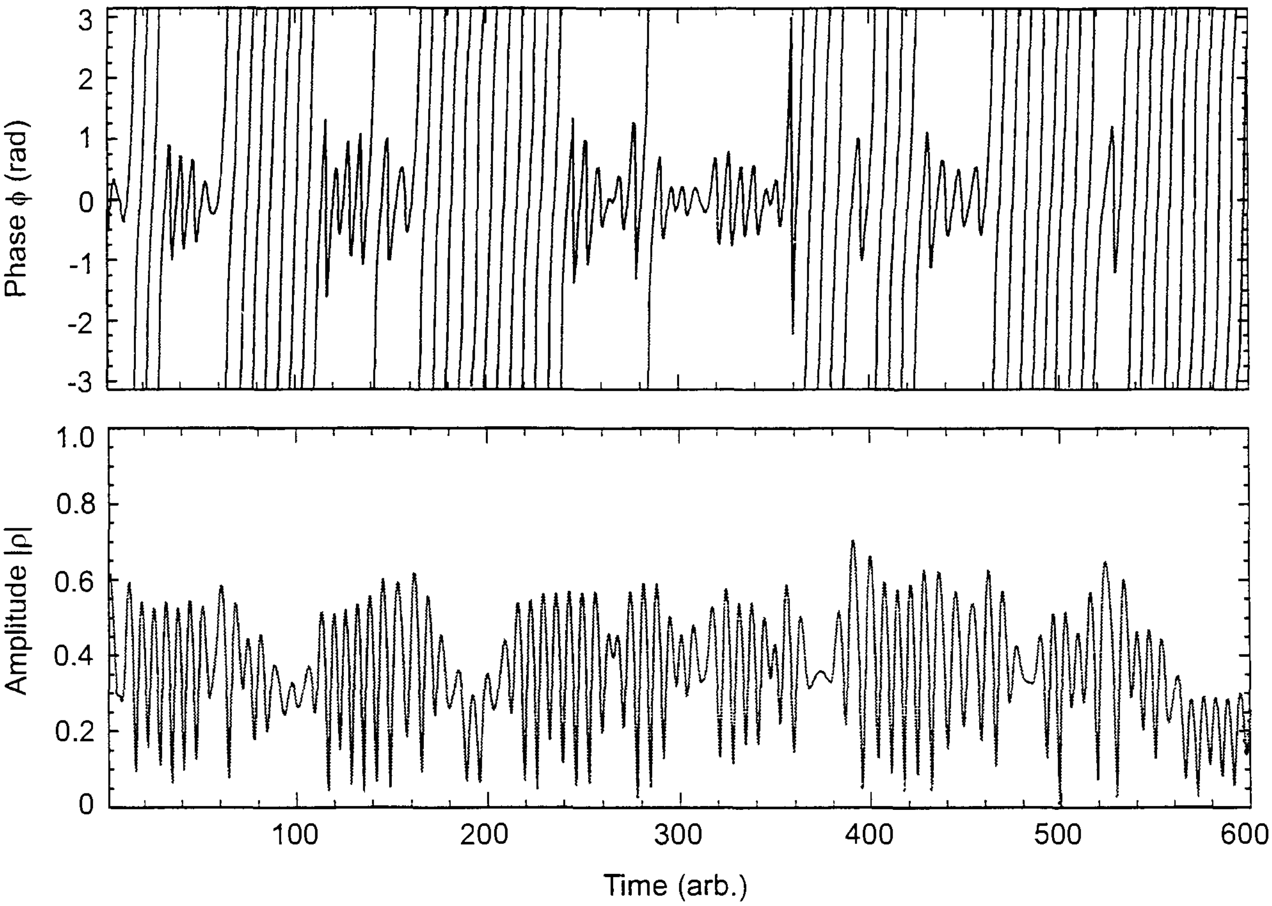


Figure 7: Simulated phase and amplitude signals from a 2D physical optics code using a random surface perturbation with a strong single frequency component, $k_p/k_o = 0.2$, $k_w/k_o = 0.05$, $\sigma/\lambda = 0.1$ *and an antenna misalignment of* $|\theta_1 - \theta_2| = 5^\circ$ *and a beam radius of* w/λ *=5.*

Fig. 7 shows a small segment of the simulated ϕ and A signals obtained using a reflecting layer containing surface perturbations with a k spectrum shown by the dashed line in Fig. 8(a) (normalized to $k_o = 2\pi/\lambda$). The k spectrum has a peak at $k_p/k_o = 0.2$ and a width $k_w/k_o = 0.05$. The rms perturbation amplitude is $\lambda/10$ while the transmit and receive antennas are misaligned by $|\theta_1 - \theta_2| = 5^\circ$ with a beam radius at reflection of 5λ.

The corresponding Fourier spectra for the phase ϕ and amplitude A signals are shown in Fig. 8(a) (single sided) together with (b) the phase-amplitude γ^2 coherence and (c) cross-phase spectra, (d) phase distribution (pdf), (e) amplitude distribution (pdf) and (f) the double-sided spectra of the phase (dashed) and complex amplitude signals. Both the ϕ and A spectra reproduce the Doppler shifted peaks with strong coherence and $\pm\pi/2$ phase shifts of the experimental data in Fig. 6. Again the phase pdf is distinctly non-Gaussian.

The phase signal ϕ of Fig. 7 has several irregular bursts where it ramps through multiple fringes. The bursts are semi-random in length and repetition frequency. This simulation data looks exactly like the real experimental data. Note that with normal incidence (i.e. no misalignment) the same surface perturbations (MHD + turbulence) do not generate any phase runaway or bursting phenomena.

The main point here is that it is possible to replicate bursts of phase runaway in reflectometer signals from steady-state turbulence (cutoff layer perturbations), that is without recourse to any time varying growth and decay in the turbulence. This implies that some of the bursting turbulence behaviour observed in reflectometer signals *could be* just a result of the instrumentation response function.

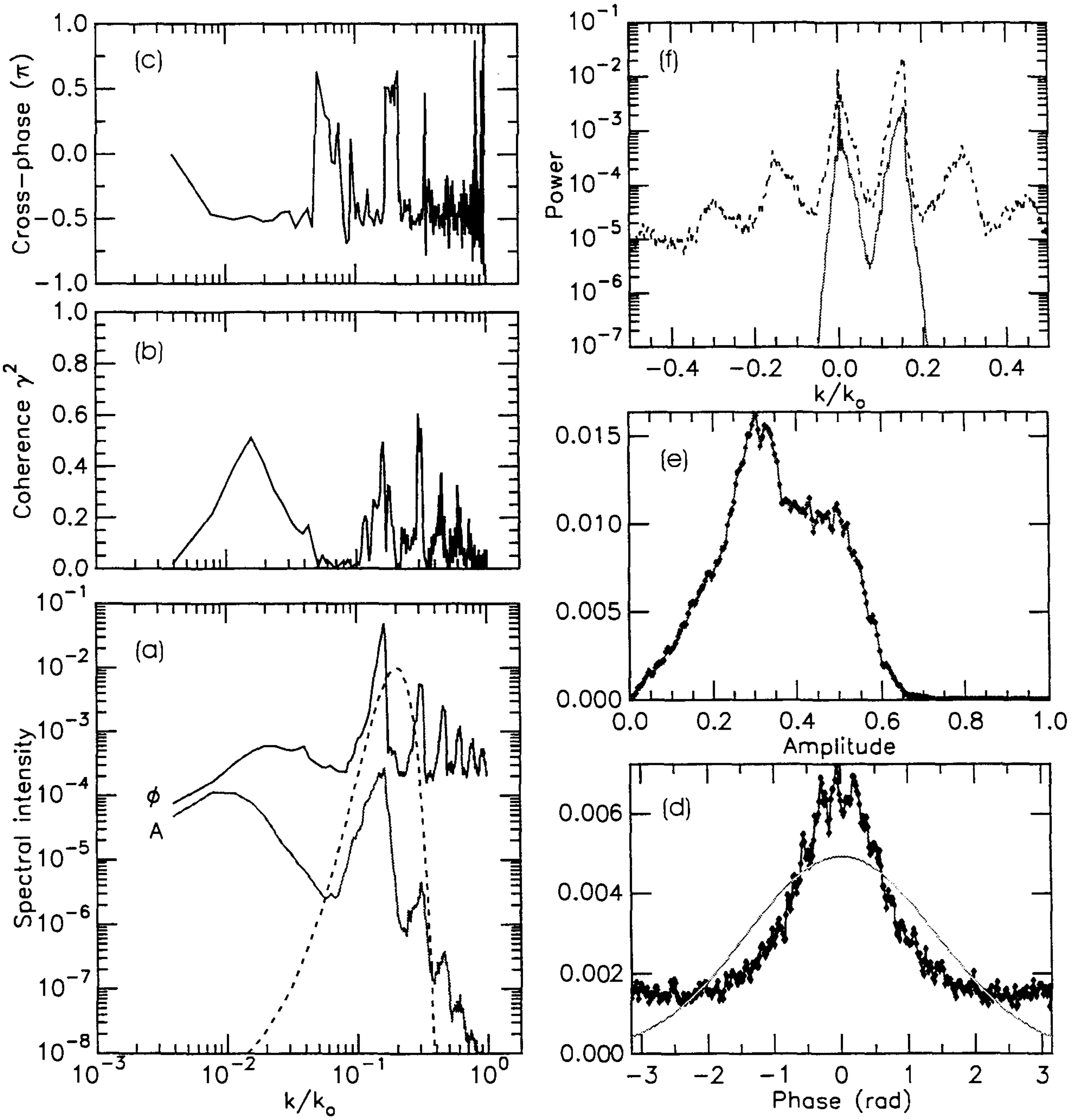


Figure 8: (a) Fourier spectra, (b) coherence, (c) cross-phase spectra of the simulation data of Fig. 7, together with (d) phase pdf (e) amplitude pdf and (f) double-sided spectra.

5. Conclusions

(1) The experimental data shows that real reflectometer signals behave in complex ways. Often they contain phase ramping/fringes on several time scales.

(2) Whenever the phase moves through a fringe there is also a modulation in (a) the mean reflected power level and (b) in the level of high frequency fluctuations in both the phase and amplitude signals.

(3) Slow phase fringes (with 's' shaping) and amplitude modulation appear to result from radial movement of the cutoff layer with a possible interference effect arising from multiple reflection between antenna and cutoff layer.

(4) Phase and amplitude signals also display fine-scale structure (with a sub-millisecond time scale) which contains intermittent bursts of phase ramping. This appears to be the classical phase runaway effect resulting from antenna misalignment.

(5) Using a 2D simulation model with steady-state turbulence and misaligned antennas it is possible to replicate the bursting or intermittent phase runaway effect in the reflectometer signal. This does not mean that all bursting turbulence observed in reflectometer signals are not real, but it does mean that without substantiating evidence from another non-reflectometer diagnostic (such as magnetics) instrumentation effects can not be ruled out.

References

[1] V.V.Bulanin & D.O.Korneev, *Plasma Phys. Rep.* **20** 14 (1994)

[2] E.Mazzucato *et al.*, *Phys. Rev. Lett.* **77** 3145 (1996)

[3] K.Shinohara *et al.*, *Jpn. J. Appl. Phys.* **36** 7367 (1997)

[4] B.Branas, M.Hirsch, J.Sanchez & V.Zhuravelev, *Rev. Sci. Instrum.* **70** 1025 (1999)

[5] E.Holzhauer *et al.*, *Plasma Phys. Control. Fusion* **40** 1869 (1998)

[6] G.D.Conway, *Plasma Phys. Contl. Fusion* **41** 65 (1999)

[7] G.D.Conway, G.Vayakis, J.A.Fessey & D.V.Bartlett, *JET report* JET-P(99)09. Submitted to *Rev. Sci. Instrum.* (1999)

[8] G.D.Conway *et al.*, *25th EPS Prague* vol. 22C 345 (1998)

[9] G.D.Conway, L.Shott & A.Hirose, *Plasma Phys. Control. Fusion* **38** 451 (1996)

Acknowledgements

Thanks to members of the JET team during the 1996-99 experimental campaigns.