Workshop on AI for Accelerating Fusion and Plasma Science

Self-consistent time series tracking for phase difference and improved density profile reconstruction scheme on the KSTAR reflectometer

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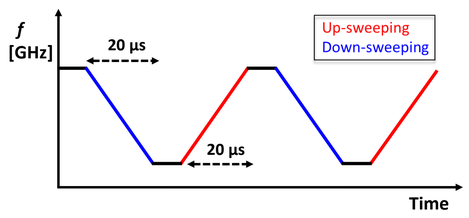
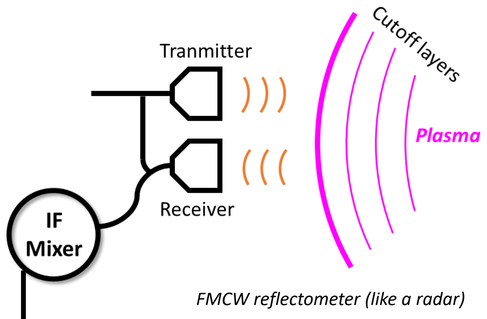
Introduction

❖ KSTAR FMCW reflectometer
(frequency-modulated continuous wave)
for density profile measurement

- Frequency modulation

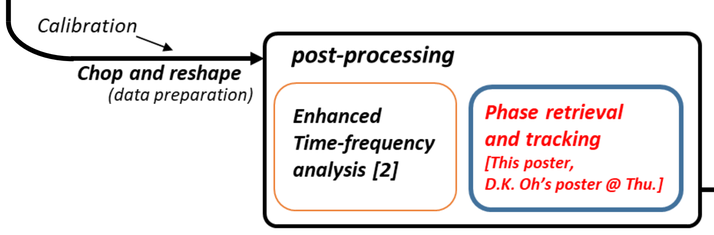




FMCW reflectometer (like a radar)

- From each plasma cutoff layer, continuous waves with swept frequency are reflected, and the phase difference (detected at **IF mixer**) occurs.
- KSTAR X-mode reflectometer (*3 sweeping bands*) can covers from edge to core plasma.

  Q-band: 32-48 GHz, V-band: 48-72 GHz, and W-band: 72-108 GHz

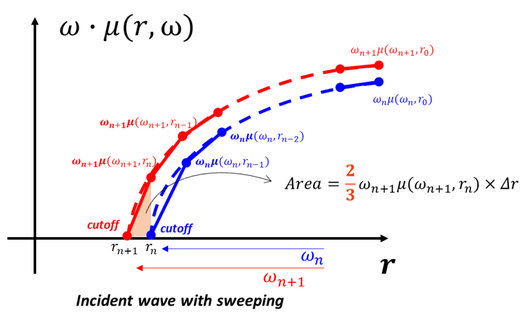


- However, in real-experiments, dedicated post-processing techniques are necessary.

Density distribution

(Inversion algorithm)

• Bottollier-Curtet algorithm [1]



The refractive index $\mu(r,\omega) = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2 \frac{(\omega^2-\omega_p^2)}{(\omega^2-\omega_p^2-\omega_c^2)}}$

The phase difference $\Delta\phi = \frac{\omega}{c}\int_{r_0}^{r_0+\Delta r} \mu dr$

$\omega_p^2 = \frac{e^2 n_e(r)}{m_e \epsilon_o}$ $\omega_c = \frac{eB(r)}{m_e}$

✓ Problems in raw signals

- ***High noise*** *(but density fluctuation actually happen!)*
- ***Multi-component signal*** *(left hand cutoff, clutters, etc.)*
- ***AM-FM***
  (Amplitude modulated, frequency modulated)
- ***ZC (Zero-crossing)***

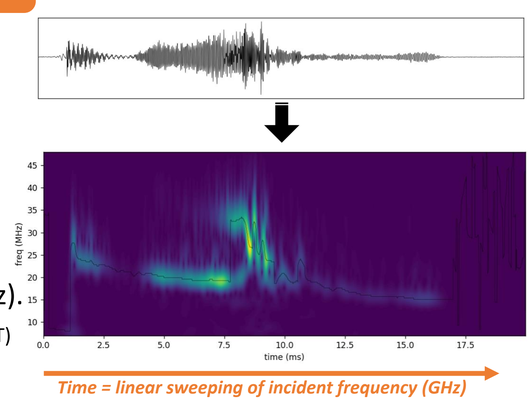
→ ***Signal processing and ML (possibly) techniques***

Time-Frequency Analysis

❖ Wavelet Transform (WT) [3]

- For the accurate analysis of instantaneous frequency (IF), wavelet transform is introduced.
- Wavelet transform is better for analyzing tempolarily localized frequency variations (cf. STFT) with a fast sampling rate (100GHz).

$z(t,f) = Ae^{i\phi}$ (complex WT, CWT)

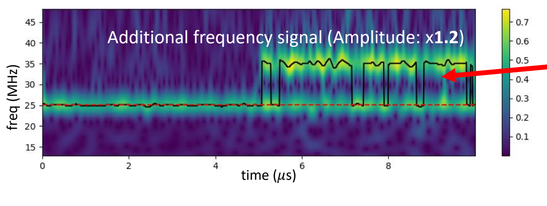


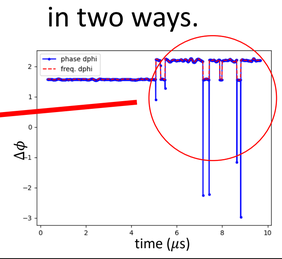
❖ Self-consistent phase difference

1) $\Delta\phi_P \equiv arg(z_t^* z_{t+1})$

2) $\Delta\phi_F \equiv \frac{2\pi(f_t + f_{t+1})}{2}\Delta t$ $\omega = 2\pi f = \frac{d\phi}{dt}$

- Given the tracked path in a CWT, one can calculate the phase difference in two ways.





Abrupt variations

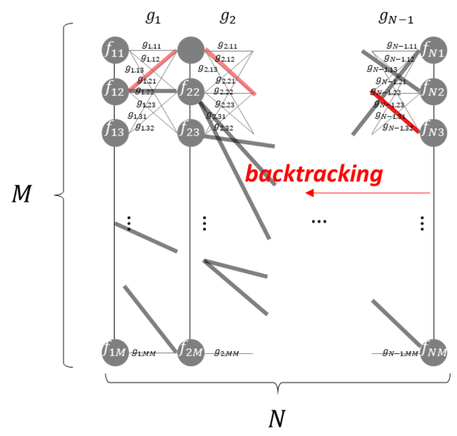
Method

❖ Viterbi algorithm [4]

$argmax_{y\in S}\, p(y_1, y_2 \dots y_N)$

Loss (or penalty) ~ log-probability

$argmin_{y\in S}\, L(y_1, y_2 \dots y_N)$



Sequential decoding

- The Viterbi algorithm (VA) estimates the maximum likelihood of the state sequence of the Markov model.
- Variants of VA are commonly used in communications, speech recognition, part-of-speech tagging, and also IF tracking of micro-doppler signals [5,6].

$$L(y_1, y_2 \dots y_N) = c_{g_1}\sum_{n=0}^{N-1}\left|\Delta\phi_p(y_n, y_{n+1}) - \Delta\phi_f(y_n, y_{n+1})\right| + c_f\sum_{n=0}^{N} f(y_n) + c_{g_2}\sum_{n=0}^{N-1}|y_n - y_{n+1}|$$

Self-consistency loss

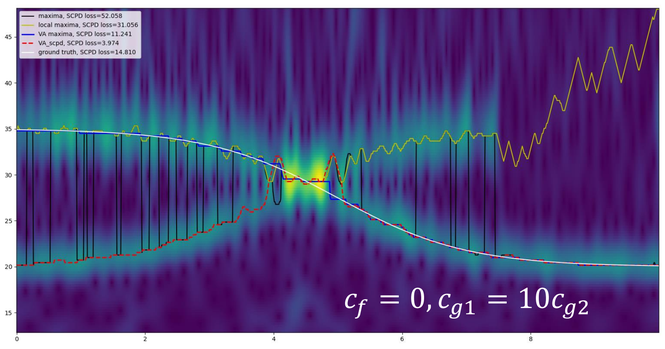
Magnitude penalty : smaller at strong mag.

Path length

Auto-term (emission): f (NxM)
Cross-term (transition) : *g* (N-1xMxM)

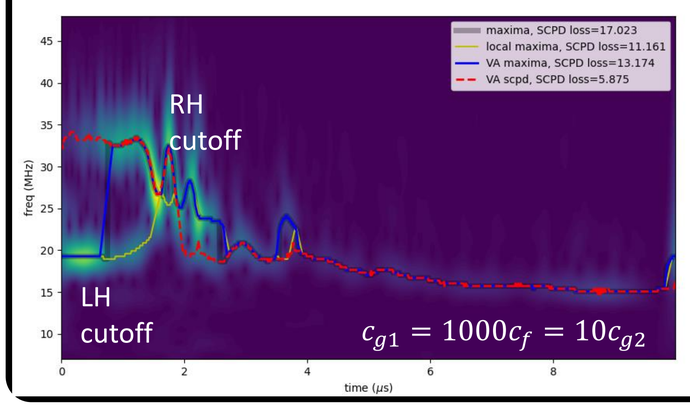
• Results

- Synthetic data



- Synthetic signals have:
  - *Gaussian white noises*
  - *random chirping*
  - *double components (AM) with a crossing*
- Even with very low SNR data, VA recovered well-connected lines without consideration of magnitude, but remains crossing region and unsplit components.

- Real FMCW reflectometer data



- In real Q-band signals, it reconstructed more likely signals after pre-parameter optimization.
- Under VA contexts, the advance of sequence tracking is expected by more physically explainable consideration. e.g. additional penalty terms

Extension to ML techniques (planned)

- Combination with the Bayesian mixture model (D.K. Oh@ Thu, poster) can suppress the fault in crossing regions and overlapped multi-components.
- Sequential machine learning models (RNN or LSTM) can be applied if there exist enough training datasets.
- Seq2seq and Attention have also applicability with full time-frequency domain information.
- In the penalty used here, density reconstruction is more automatic and faster by reinforcement learning without supervised density profiles.

Conclusion

- In tokamak density profile diagnostics, a sequential tracking method is developed for more probable time-frequency analysis.
- Viterbi algorithm with self-consistency of phase information made good paths in high noise signals.
- It is possible to extend to ML techniques for enhancing the integrity of the measurement.

Bibliography

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