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Whistler Detection Using Machine Learning

***Course**: Radiation Belt Dynamics and Remote Sensing of the Earth’s Plasmasphere*

09/27/2022

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Outline

1. Overview of Whistler Mode Waves

2. Traditional Methods of Signal Detection

3. Basic Overview of Neural Networks

4. Whistler Extraction using MSRCNN

5. Summary and Future Work

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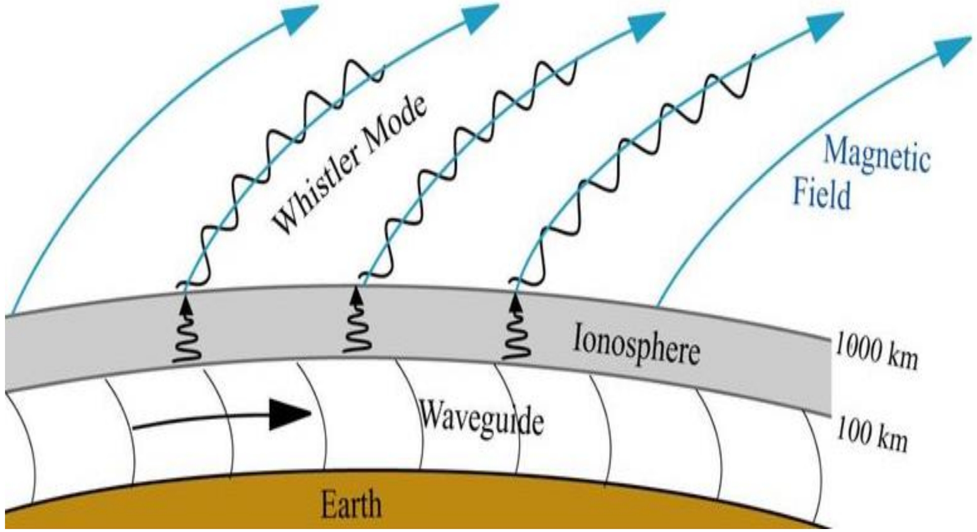
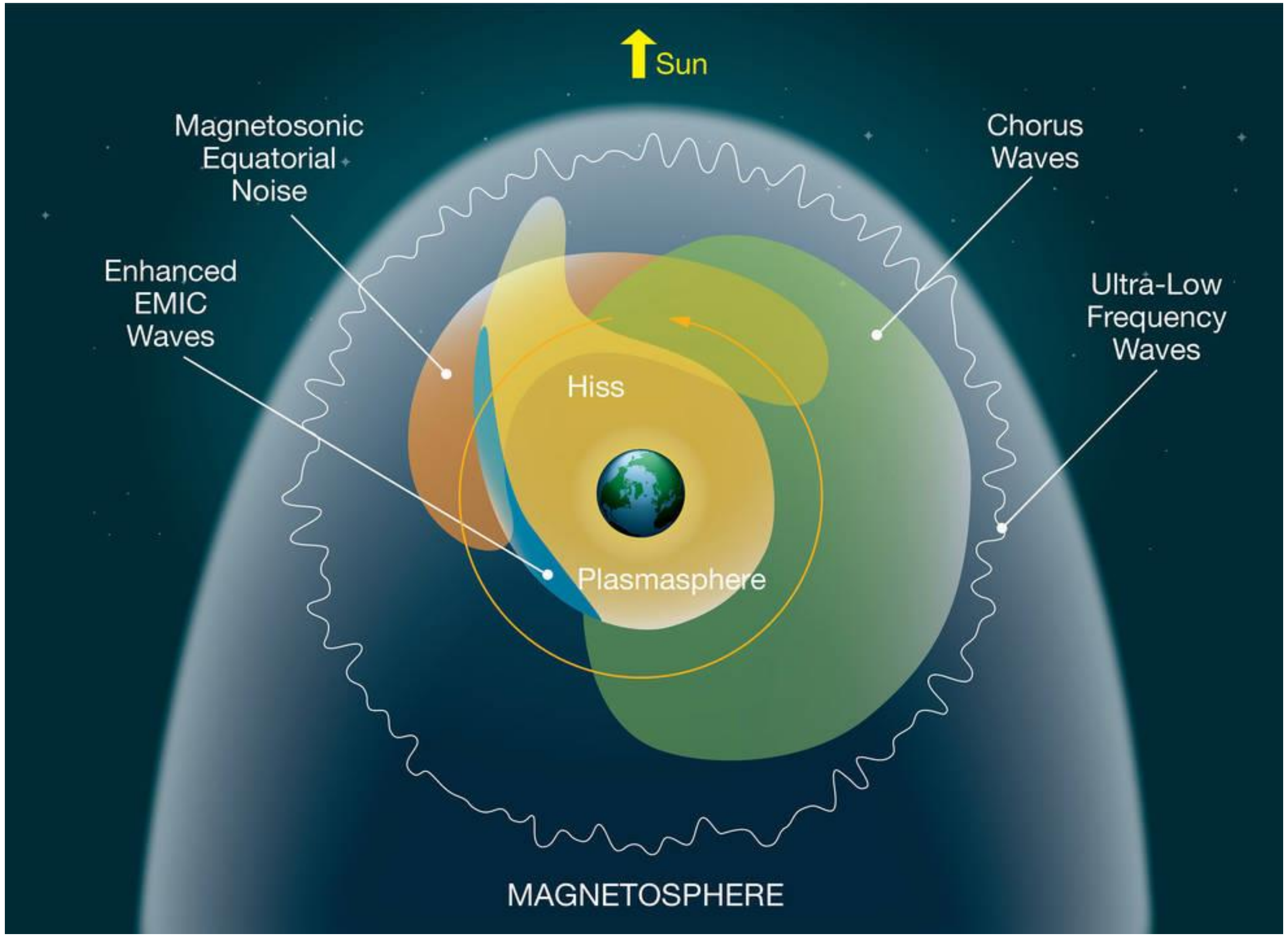
Waves in Near-Earth Space

- Radio waves in the near-Earth space environment are generated via several different processes

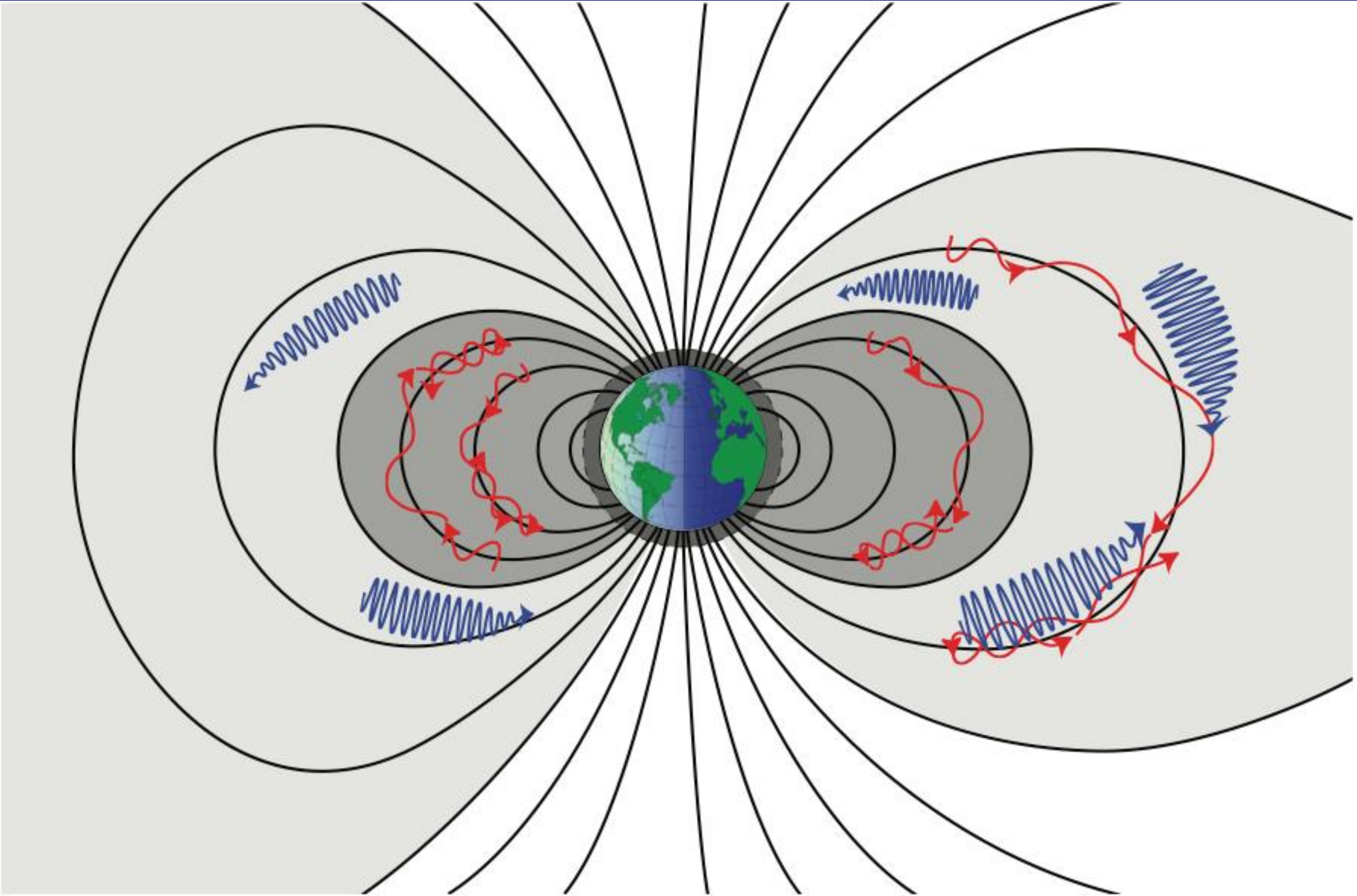
- One major classes of waves are **whistler-mode** waves in the **ELF/VLF band** (<30 kHz).





Credits: *NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith*

Inner Magnetosphere



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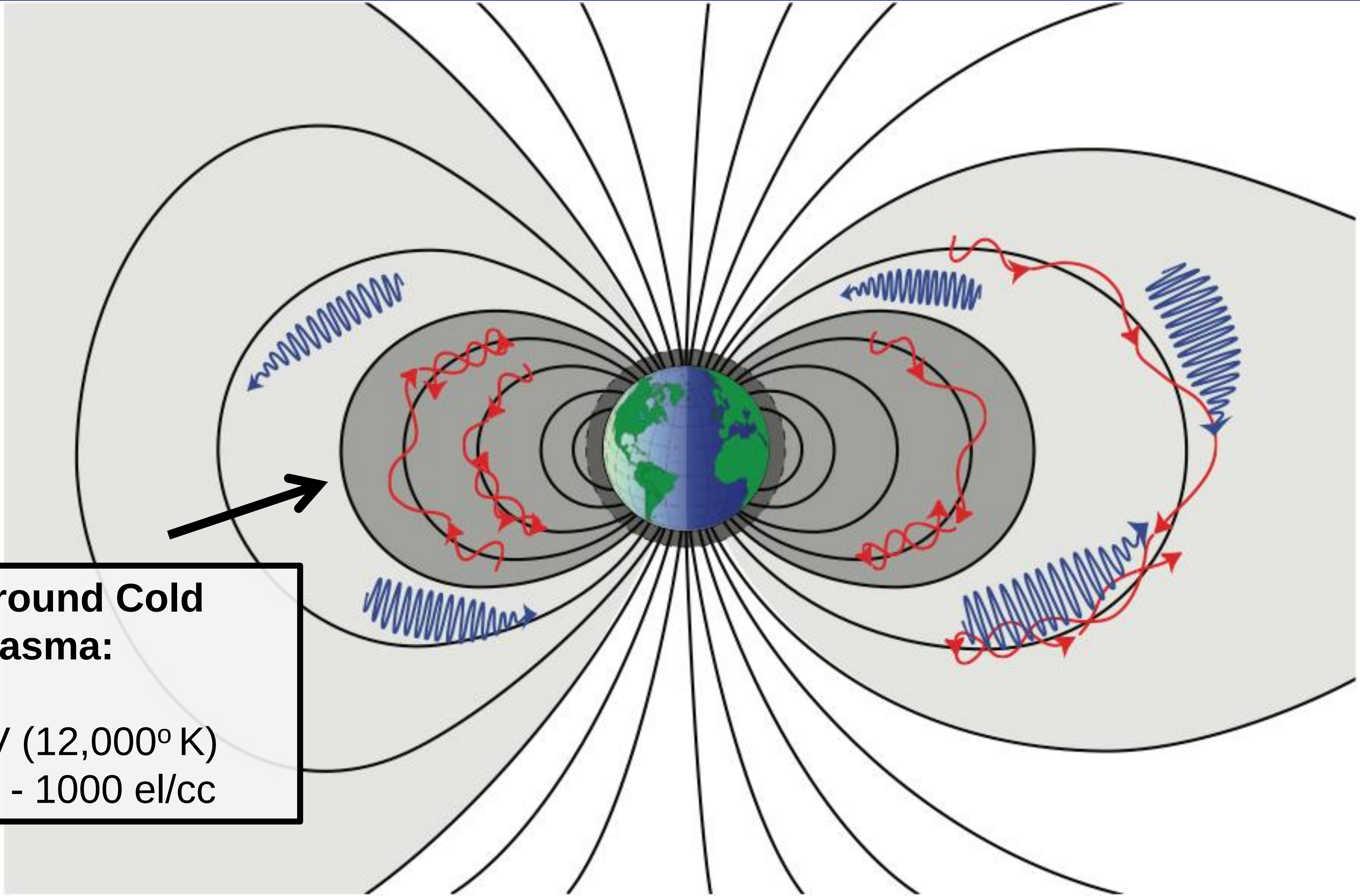
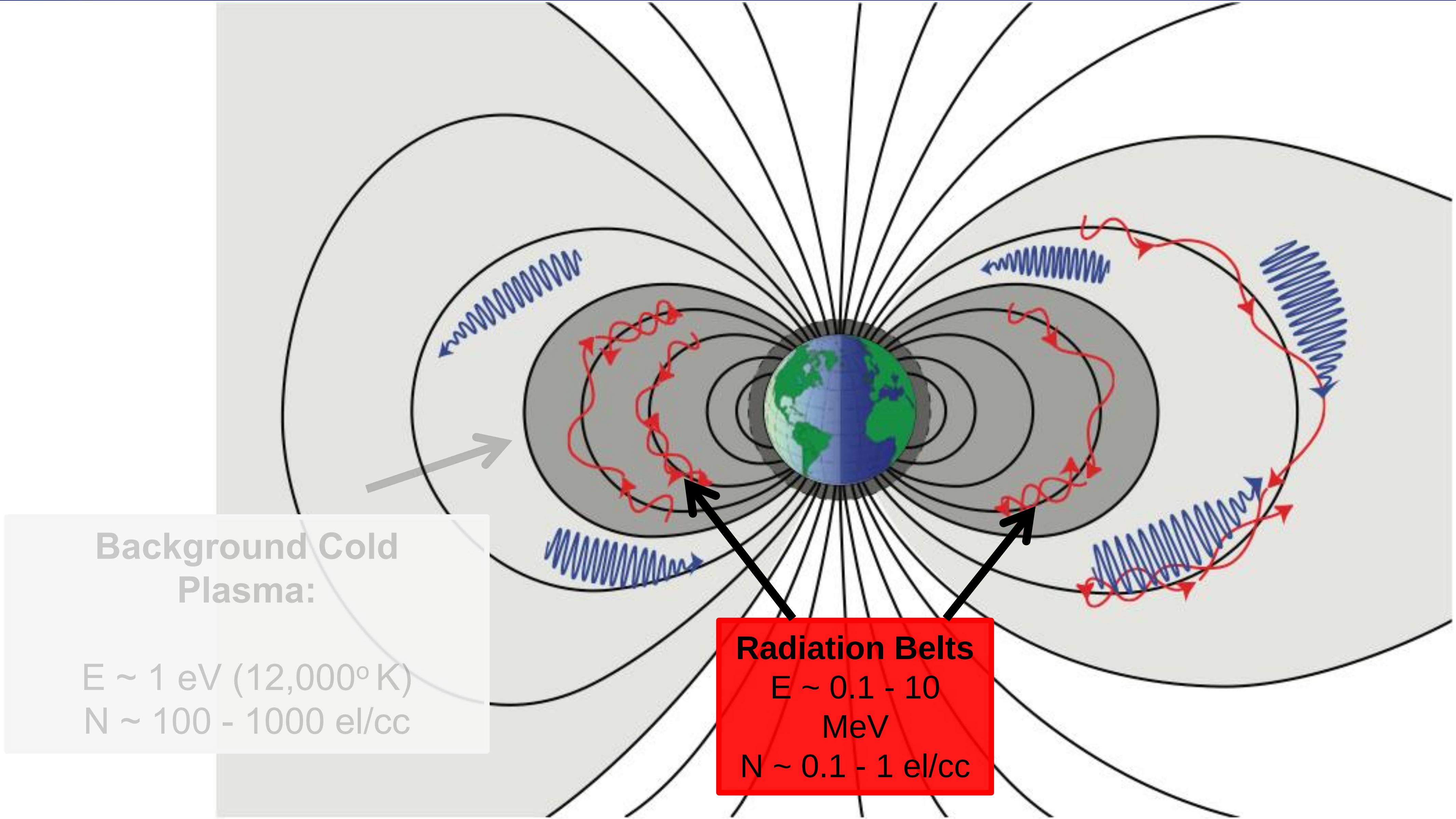


Background Cold Plasma:

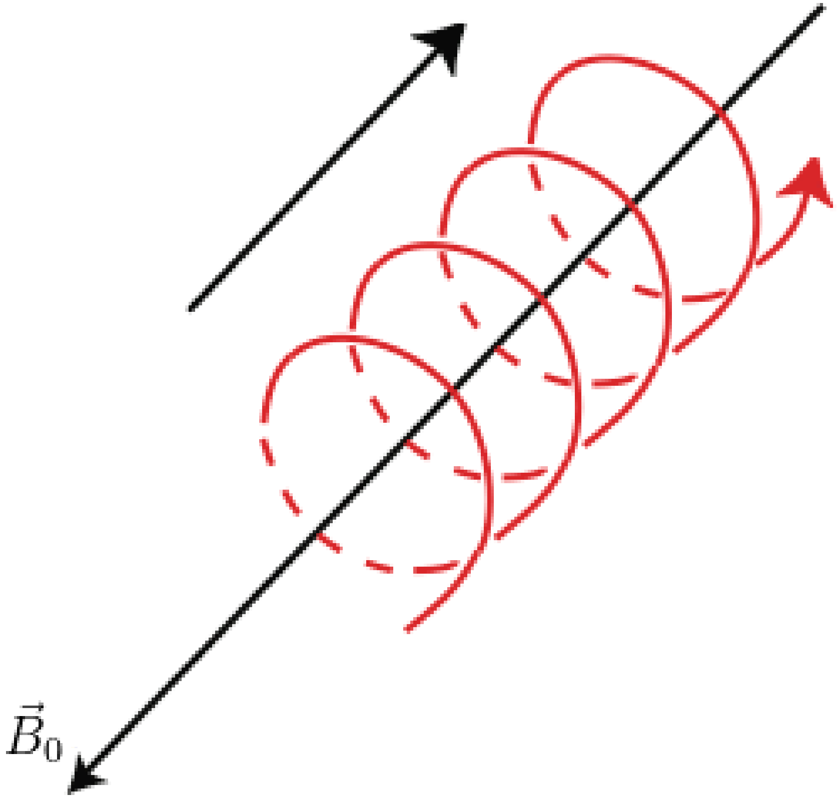
E ~ 1 eV (12,000º K)
N ~ 100 - 1000 el/cc

Inner Magnetosphere



Inner Magnetosphere

- Electron gyromotion due to geomagnetic field.



$$\omega_c = \frac{qB_0}{m}$$

Gyro-frequency

($f_C = \frac{\omega_c}{2\pi}$, 1-100 kHz range)

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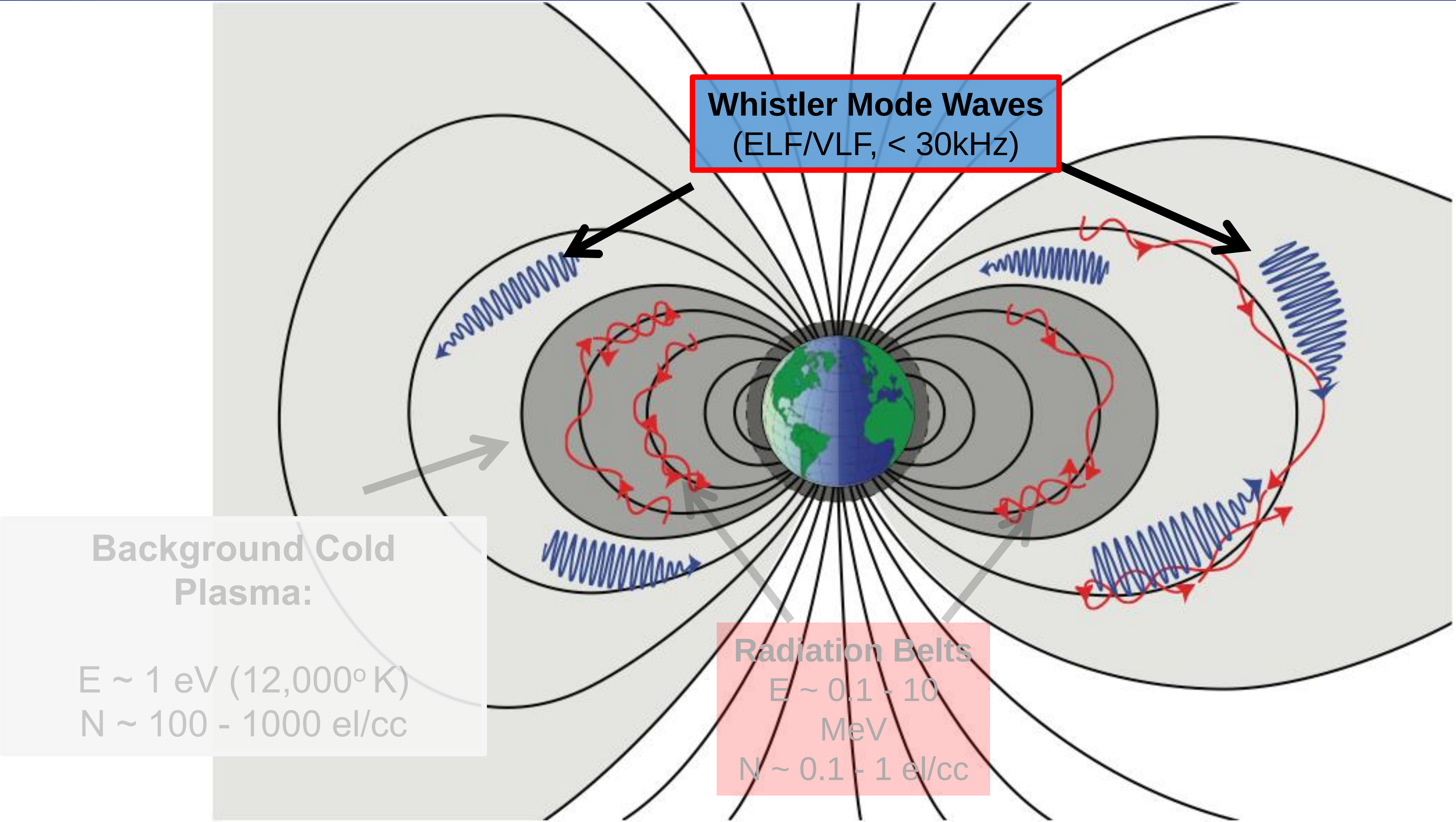
Inner Magnetosphere



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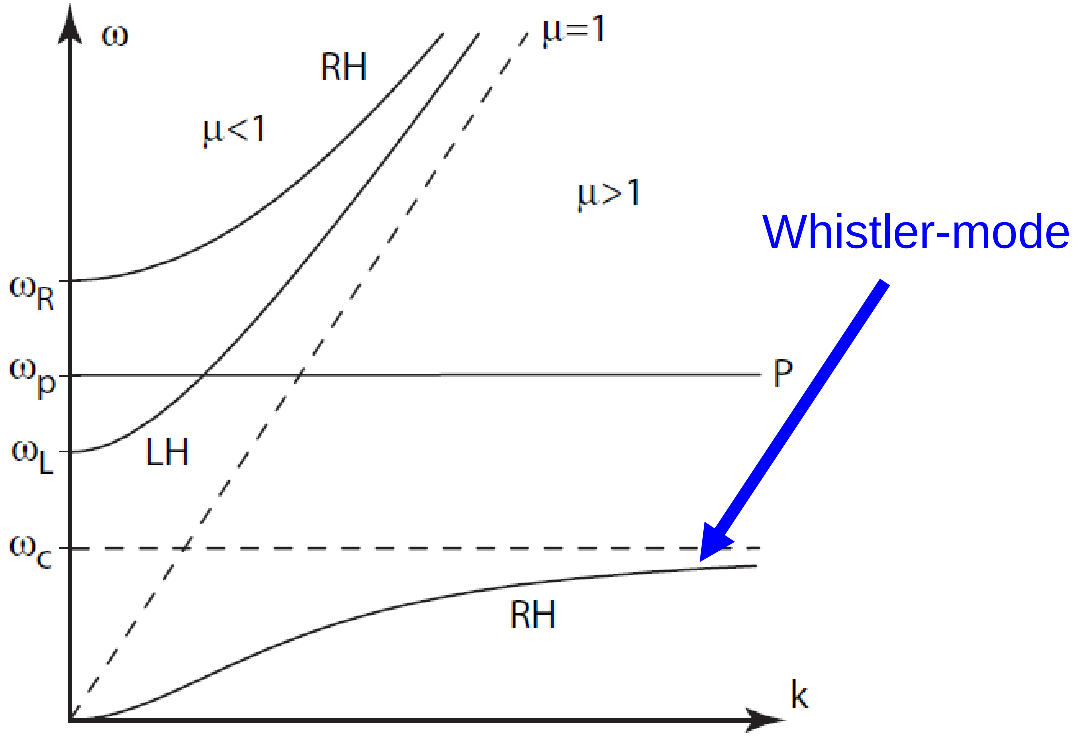
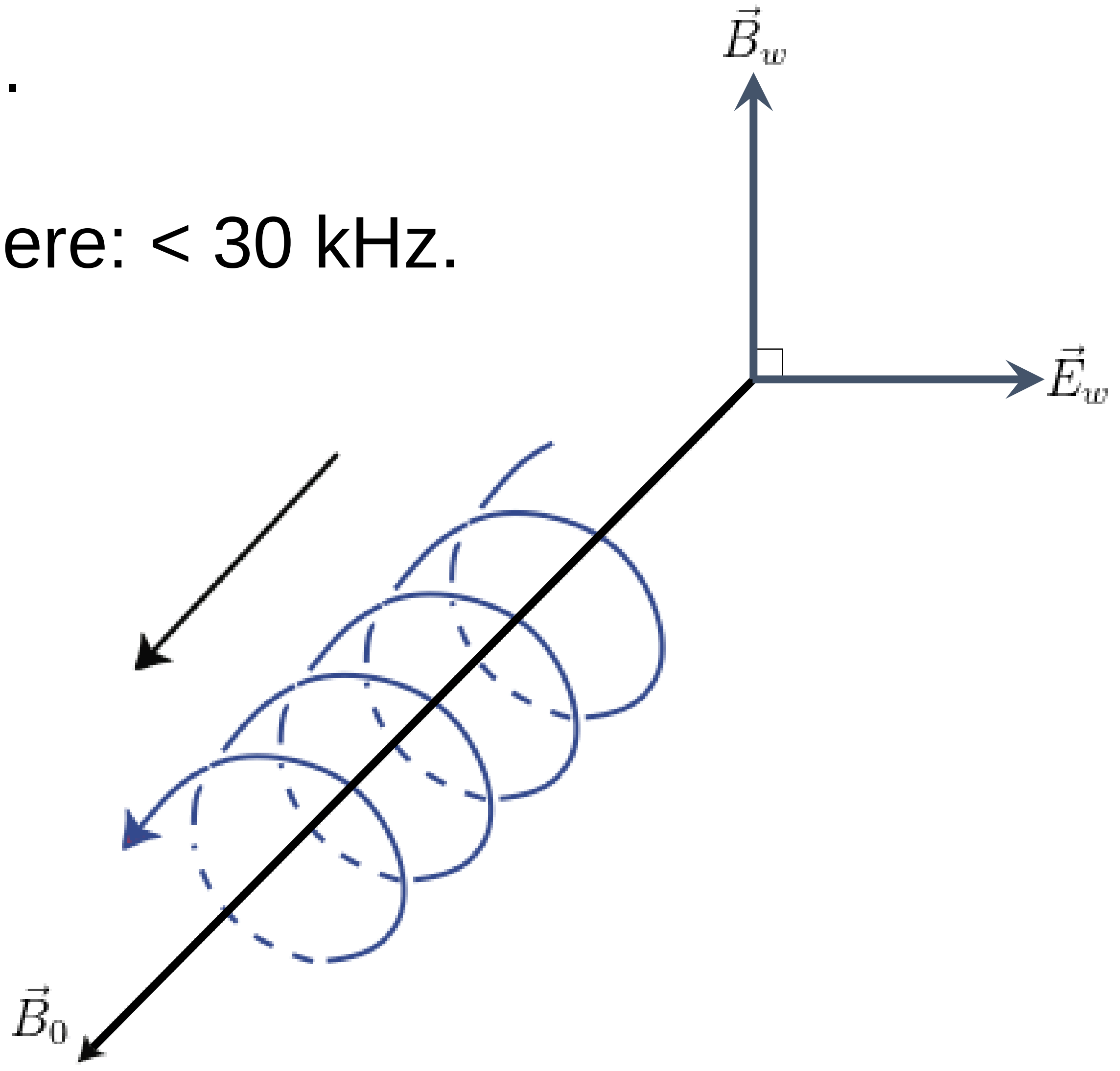
Whistler Mode Waves

- Exists only in magnetized plasmas.
- ELF/VLF range in the magnetosphere: < 30 kHz.





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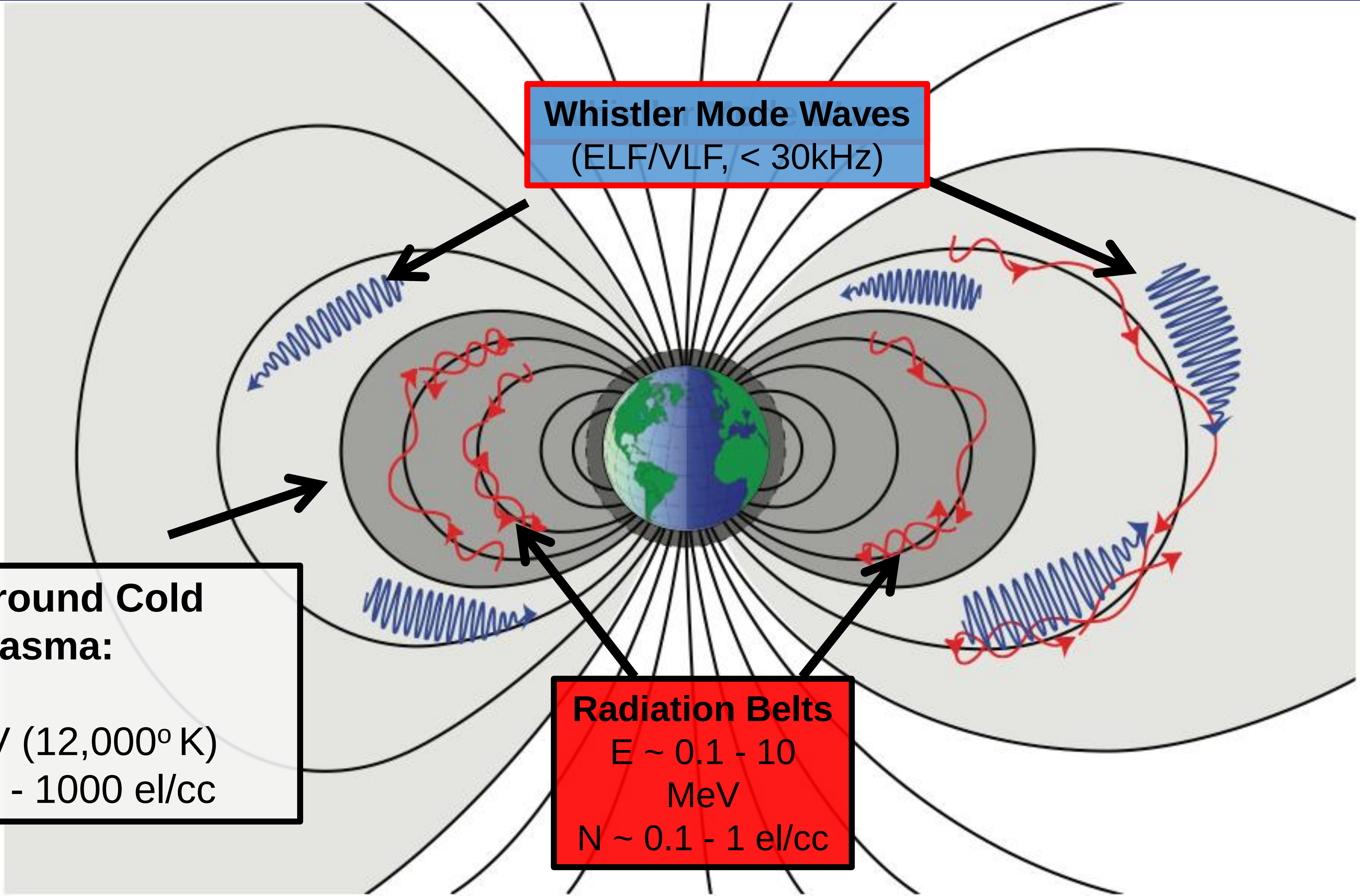

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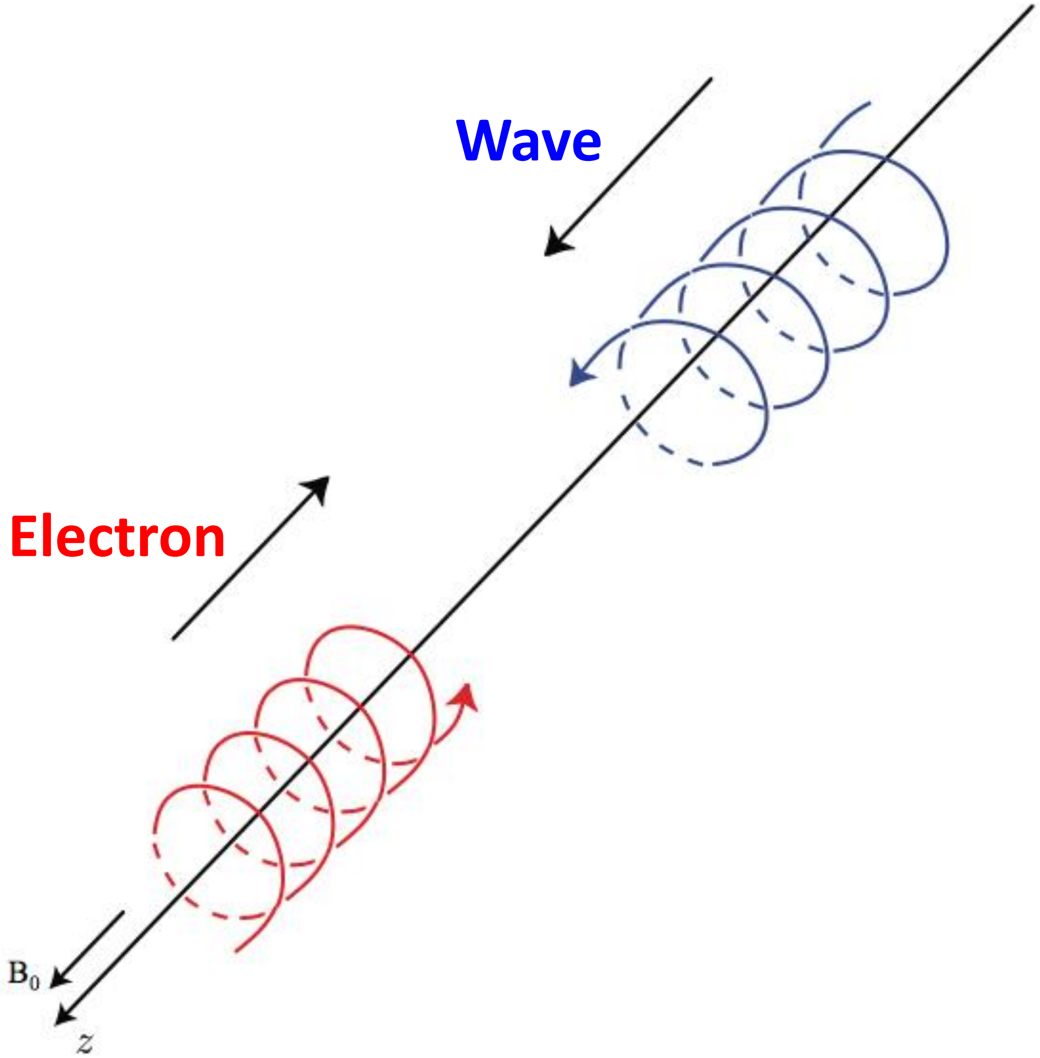
Wave-Particle Interactions

- Whistler-mode Waves can interact with electrons via Doppler-shifted-cyclotron resonance (gyro-resonance).
- Resonant electrons can transfer large amounts of energy to/from waves.
- Understanding characteristics of whistler-mode waves is crucial to space weather modeling!



Classes of Whistler Mode Waves

Naturally Sourced:

- Chorus
- Hiss
- Lightning-Whistlers

Artificially Sourced:

- VLF transmitters + Triggered Emissions

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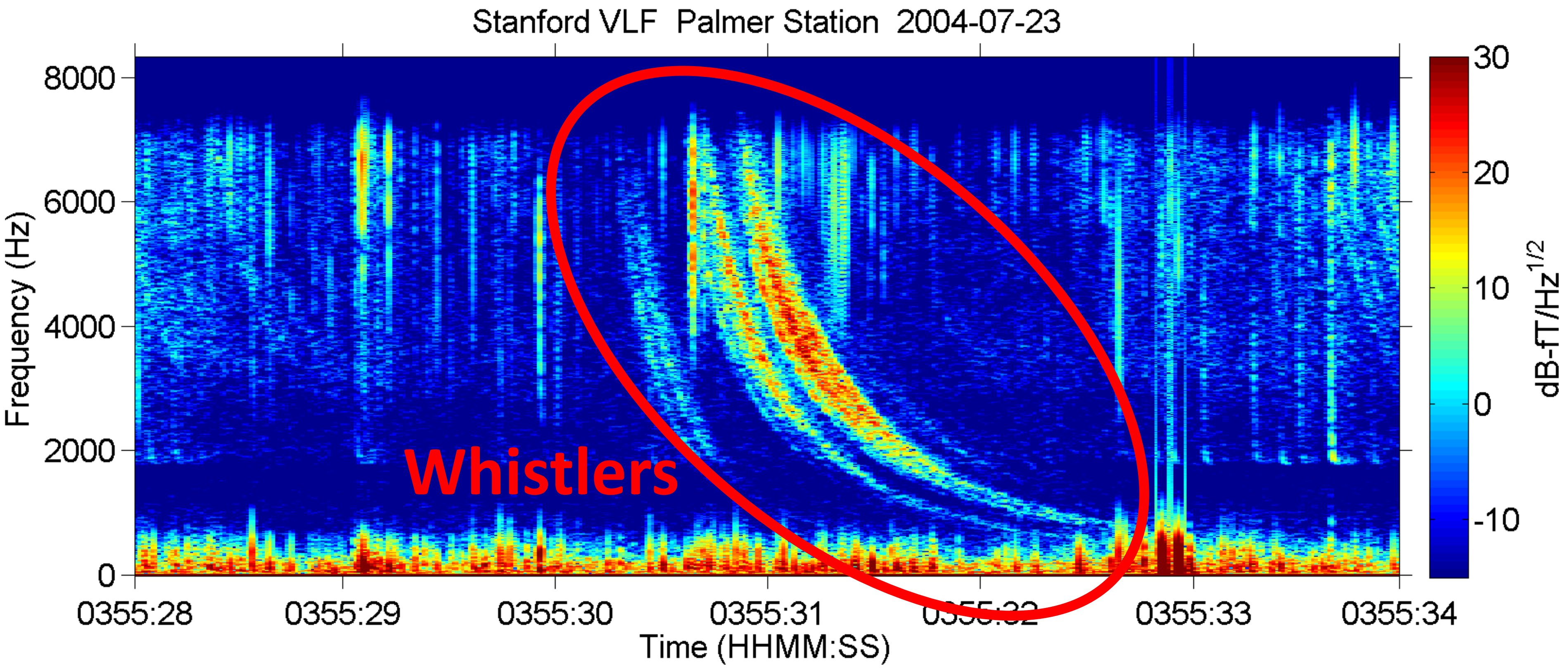
Lightning Whistlers

- ELF/VLF waves are typically analyzed using spectrograms (STFT).
- Whistlers are observed on a spectrogram as descending tones.



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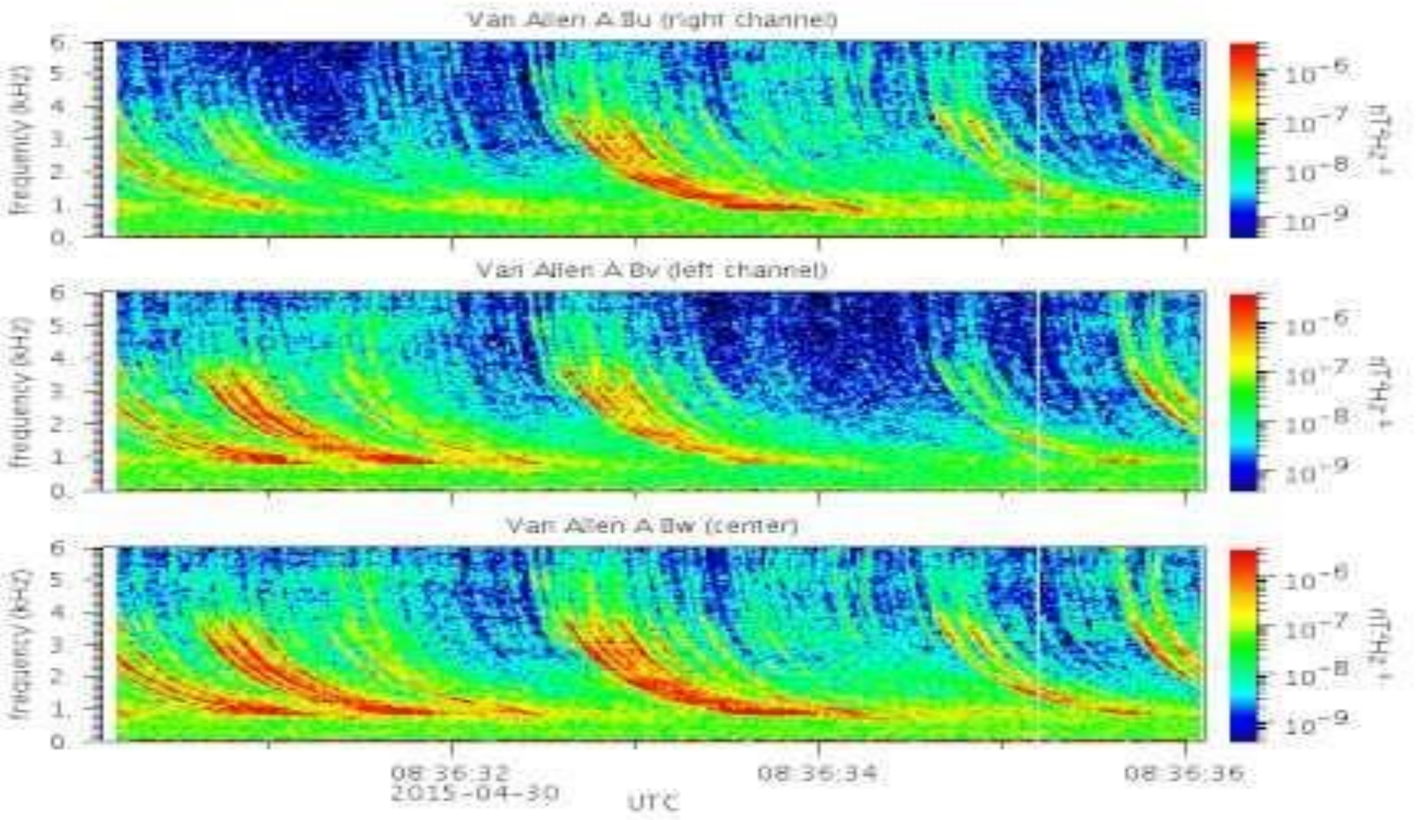
Lightning Whistlers

- Whistlers are in the VLF band (<30 kHz).
- Acoustic waves in the VLF band are audible.
- The name “whistler” reflects the descending whistle-like sound when listened to.

From RBSP in 2015 (https://youtu.be/ZVlZ5ikvet8)



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Very Brief History of Whistlers

- First comprehensive investigation of whistlers was by *Storey, 1953.*

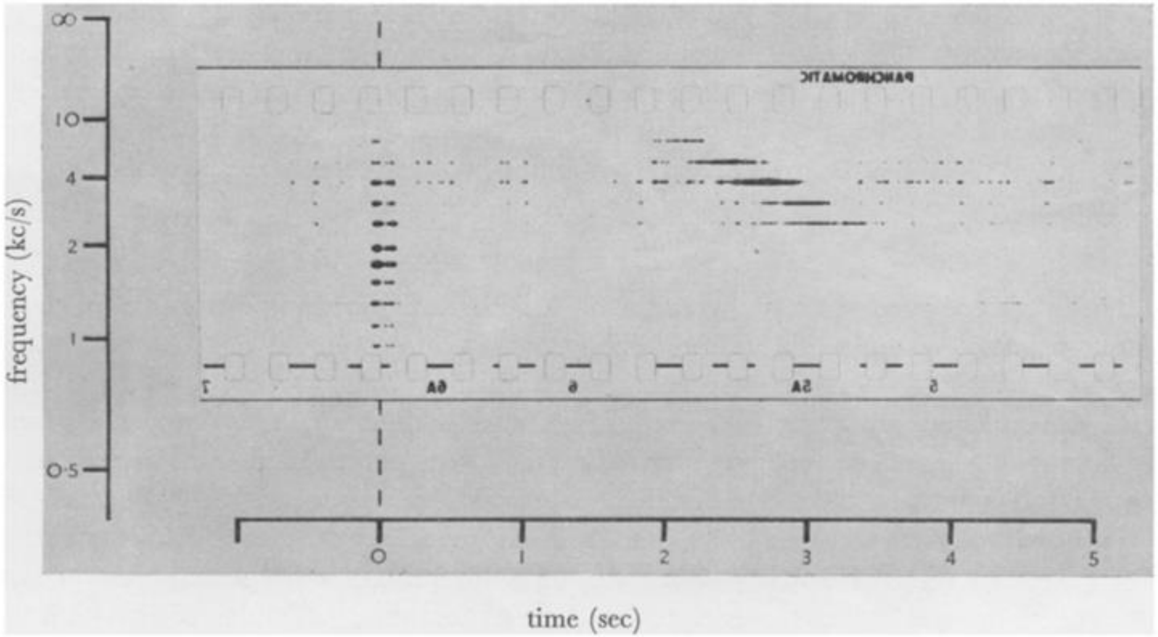

FIGURE 1. Sound spectrograph record of a whistler following an atmospheric click.

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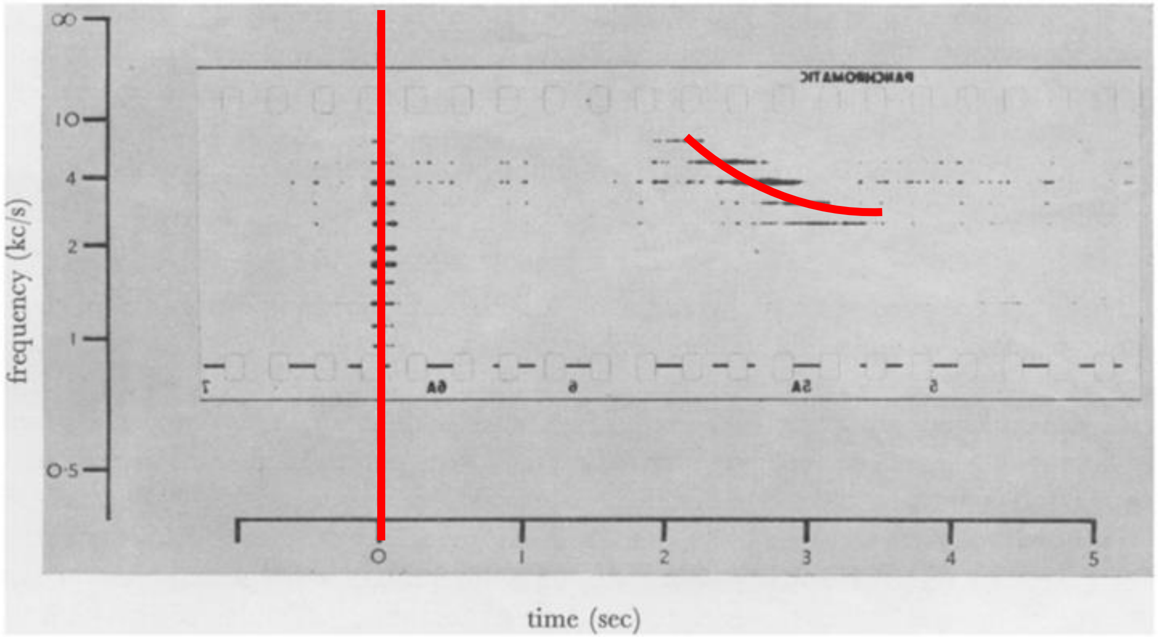

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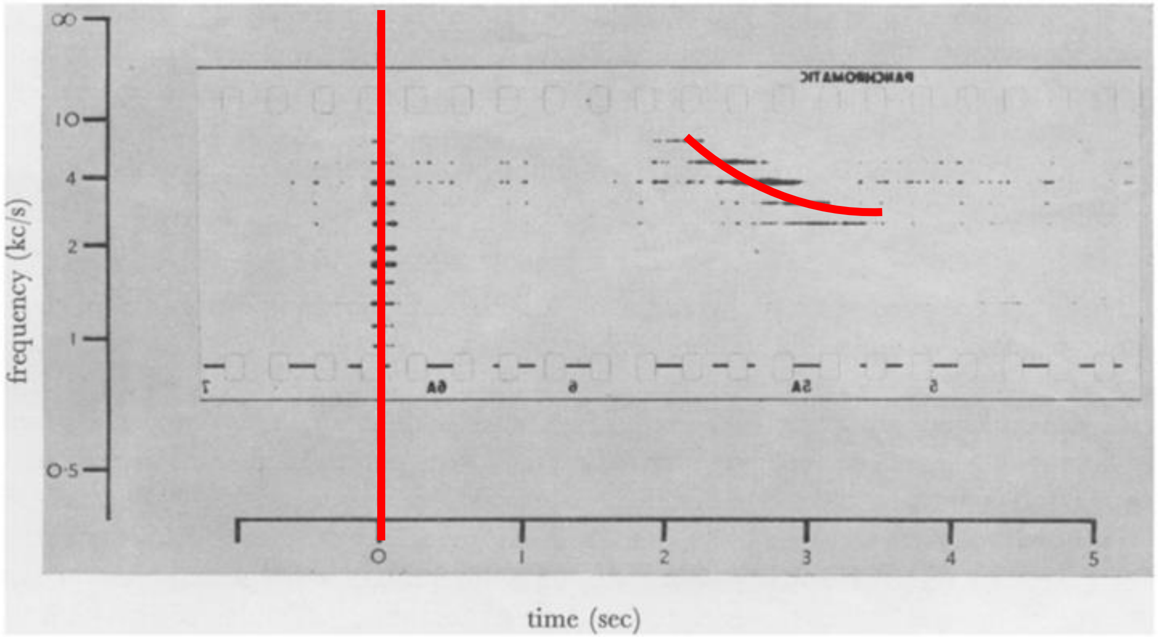

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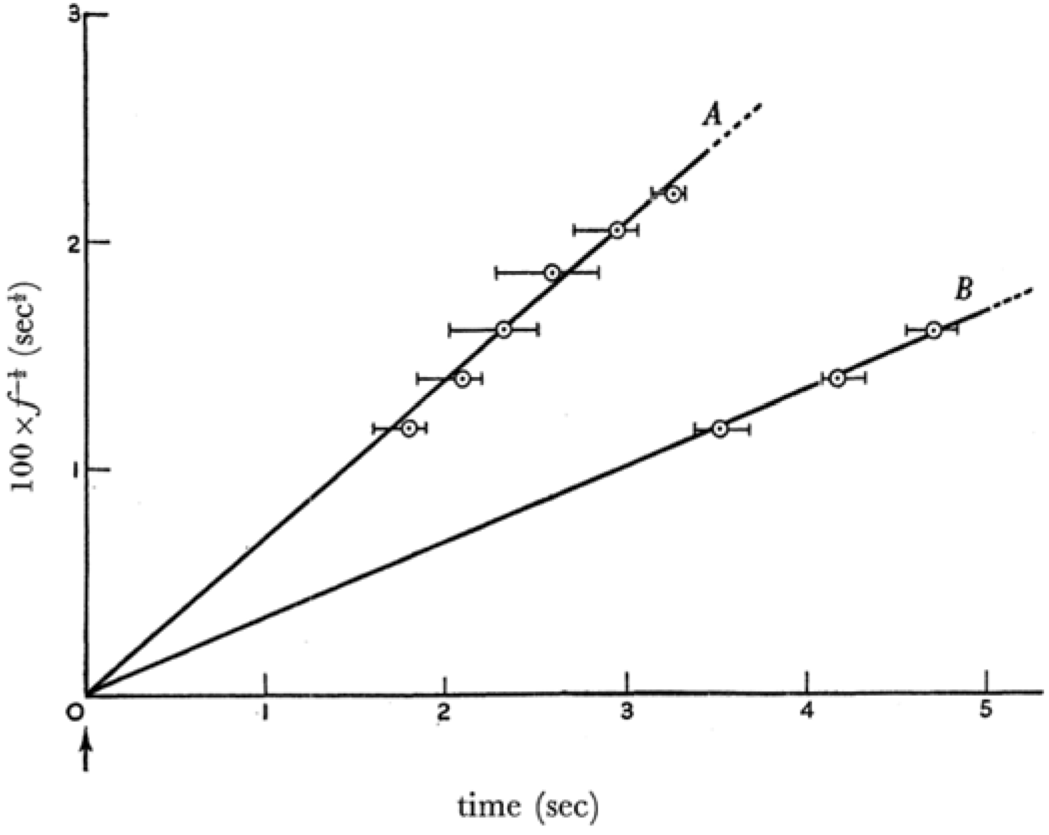

Very Brief History of Whistlers

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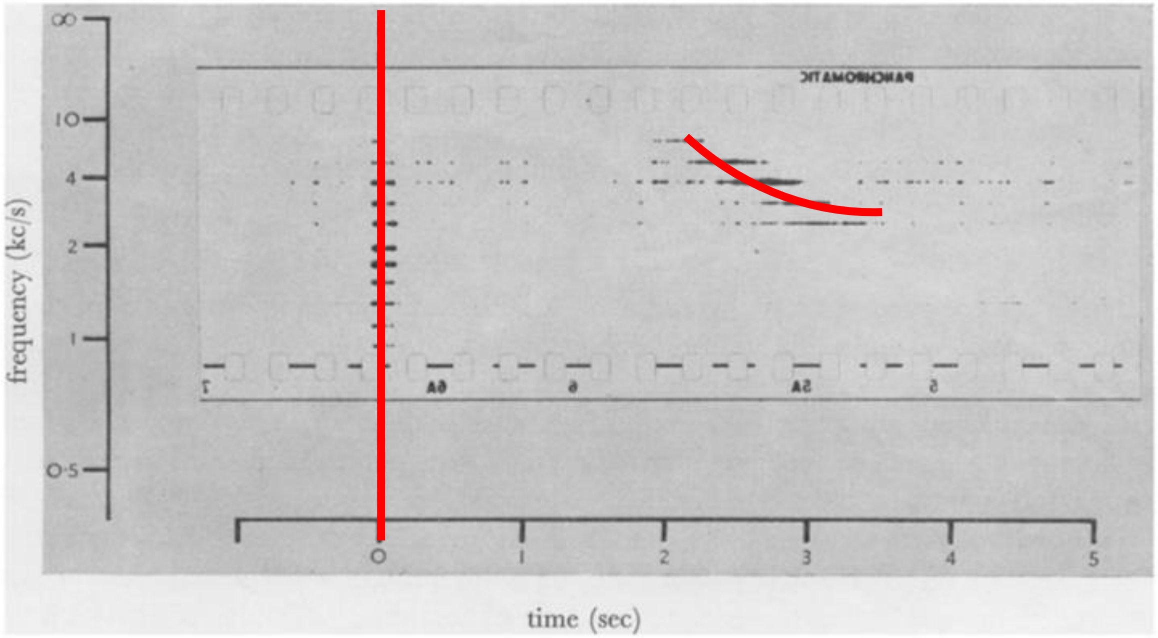
As already mentioned, the theory of Barkhausen & Eckersley predicted that the frequency (f) in the whistler should be related to the time (t) after the original lightning flash by the expression

$$t = D \times f^{-\frac{1}{2}}.$$



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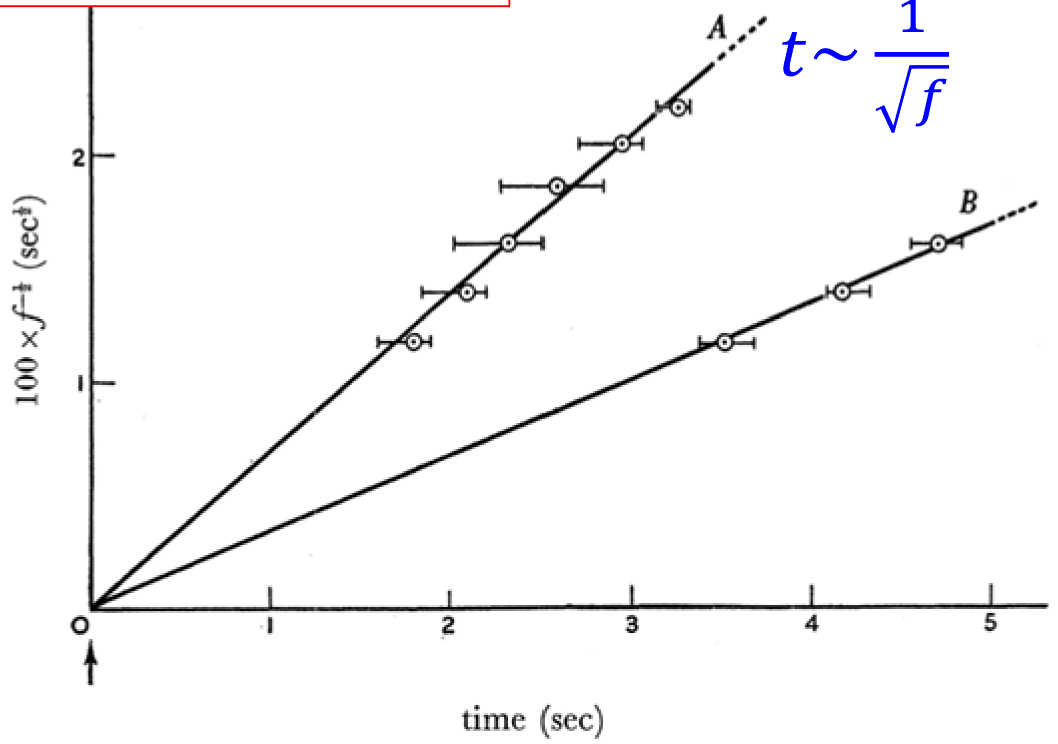
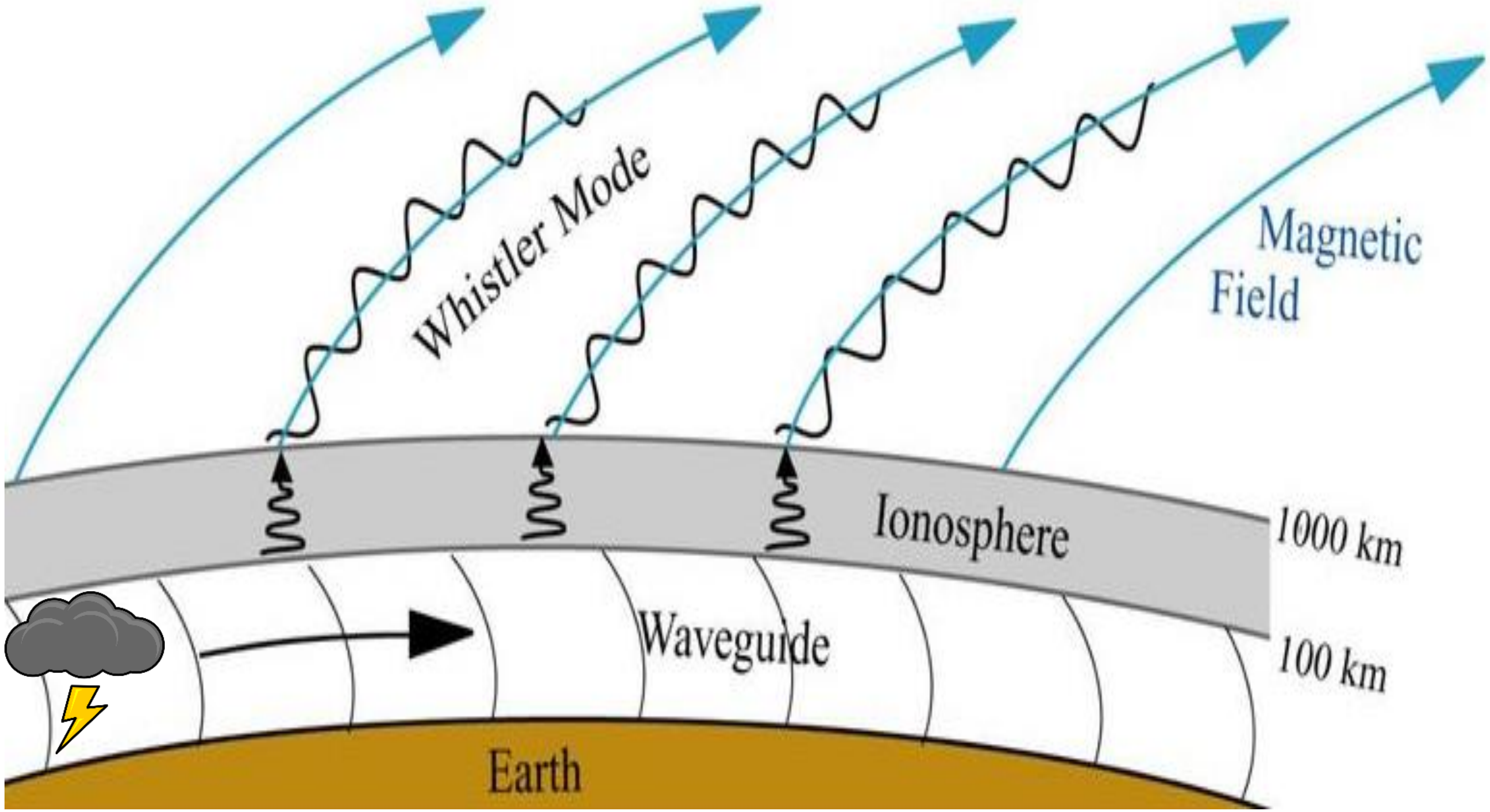


Where do Whistlers Come From?

- Lightning EMPs (sferic) can leak into the magnetosphere and propagated in the whistler-mode:



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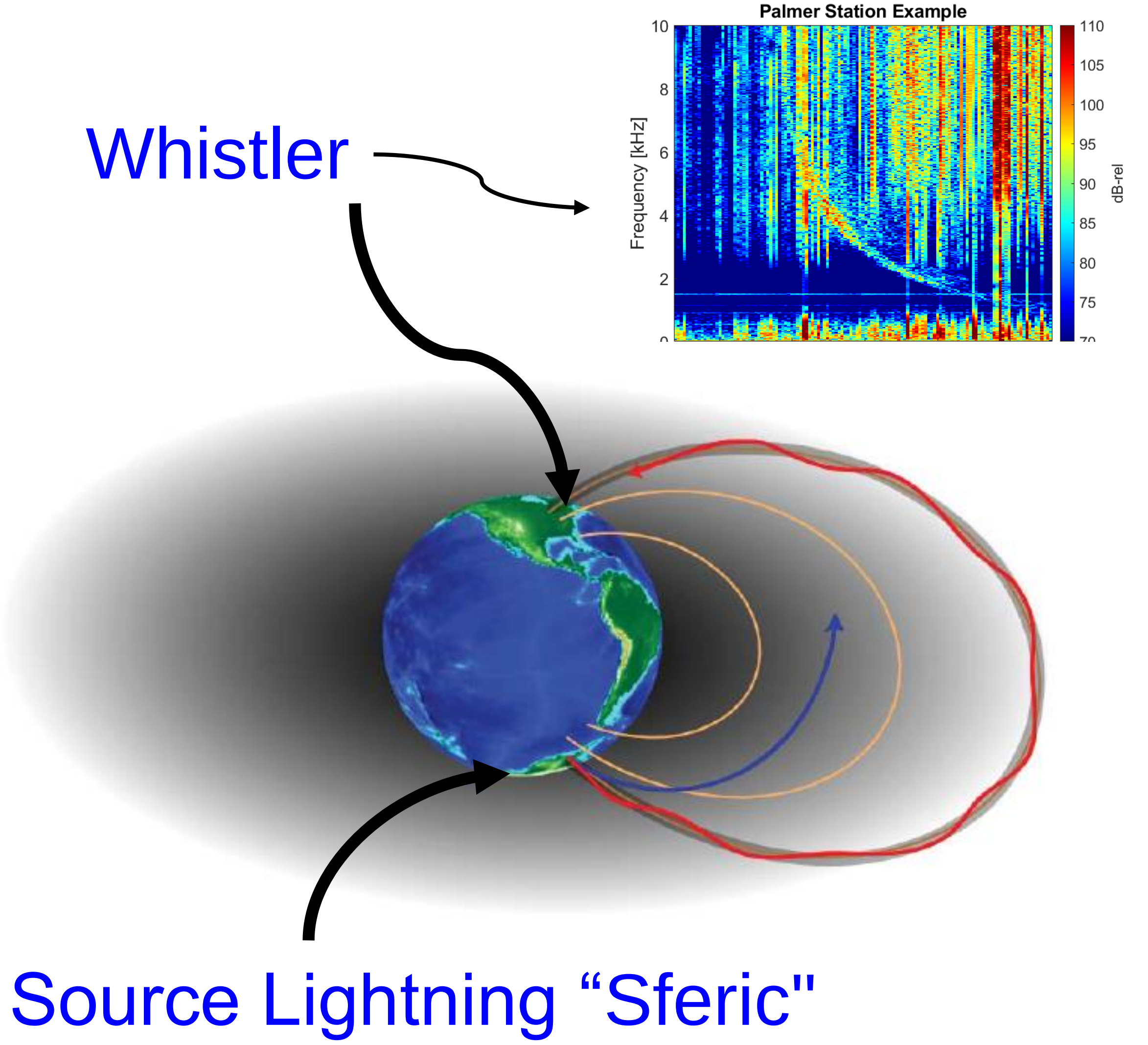

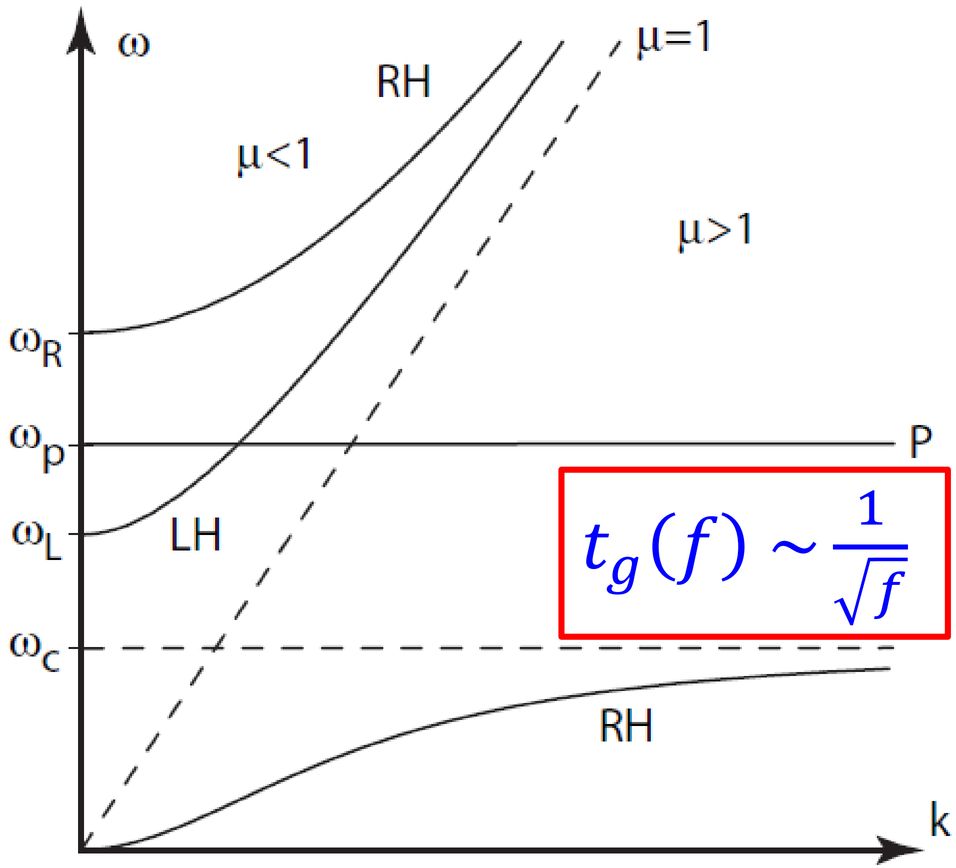

$$t_g(f) \sim \frac{1}{\sqrt{f}}$$

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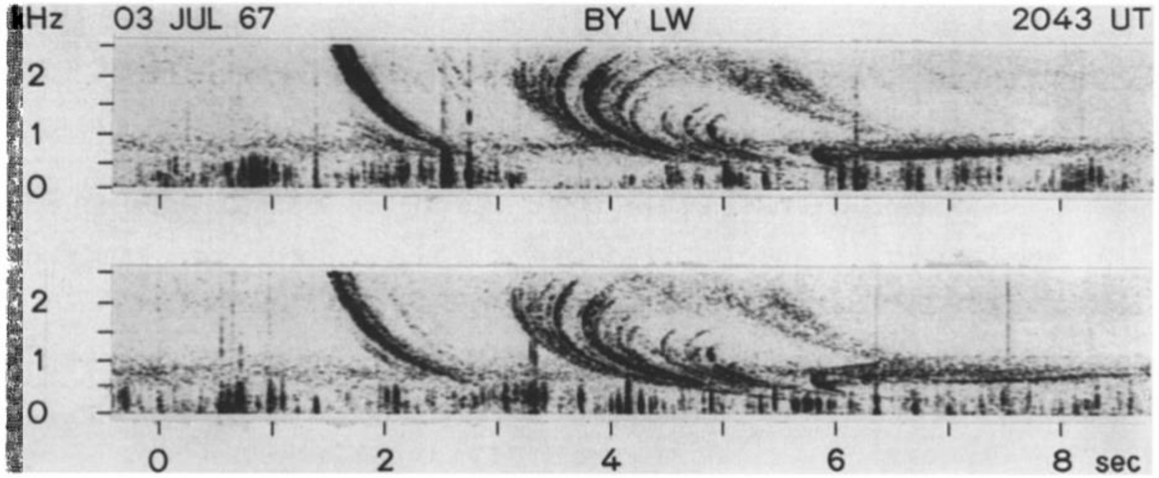
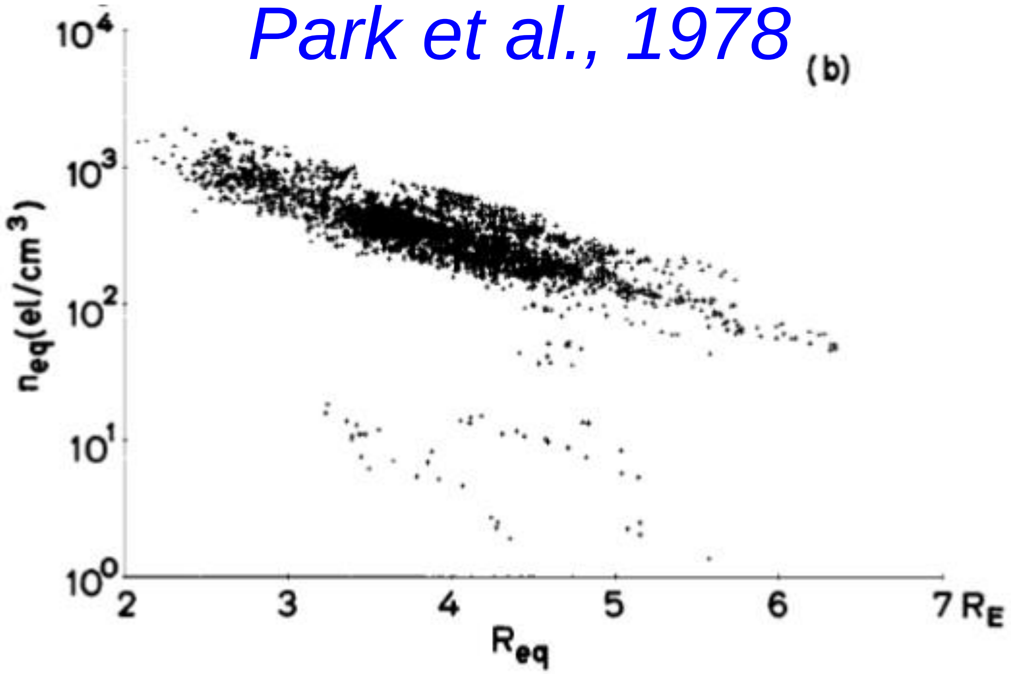
Whistlers: Plasmasphere Remote Sensing

- The whistler shape (and/or "nose frequency") can be used to remotely determine the plasmasphere's electron density… $t_g \sim \sqrt{N_e}$

Carpenter, 1988



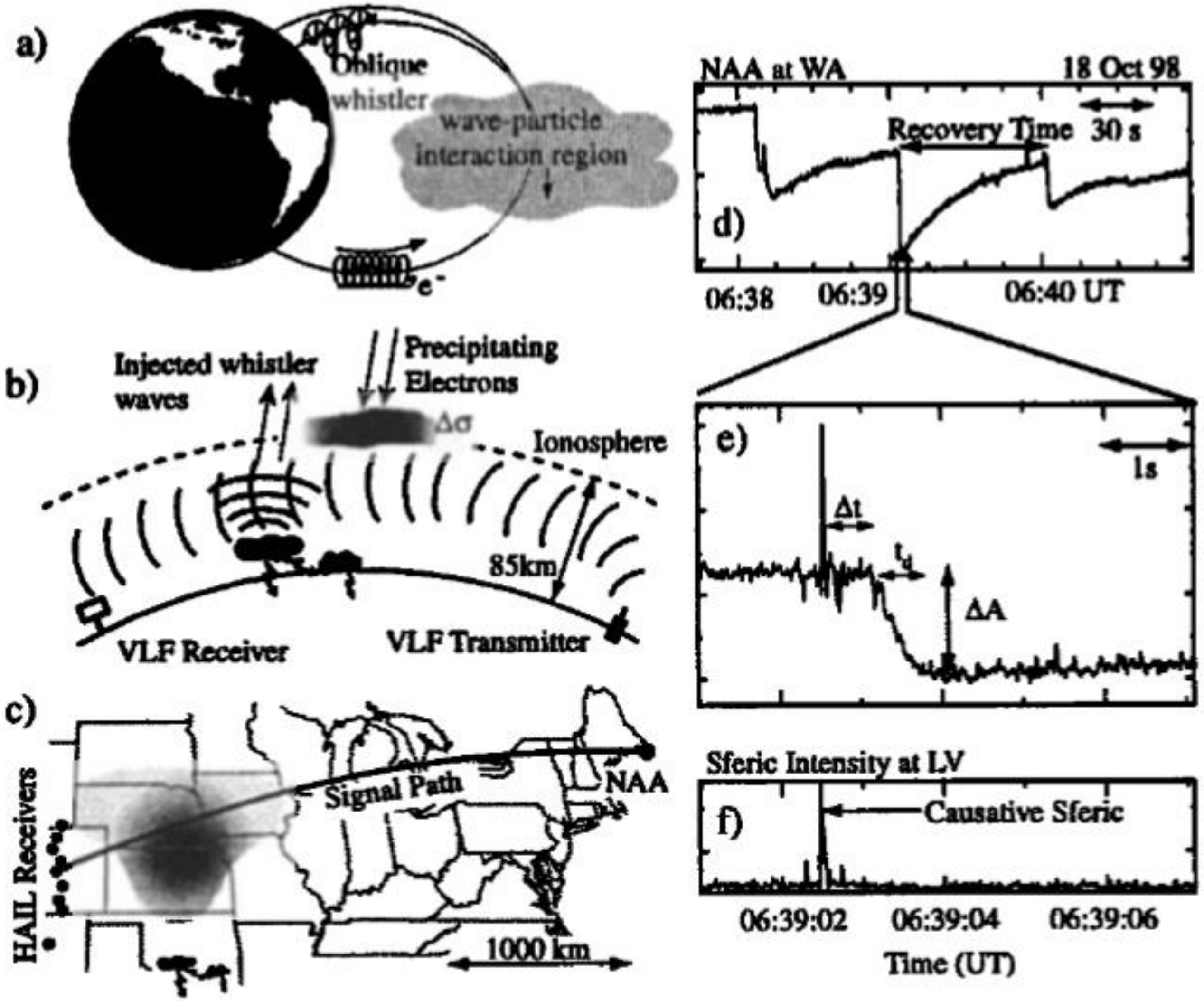
Park et al., 1978



Whistlers: LEP Events

Johnson et al., 1999

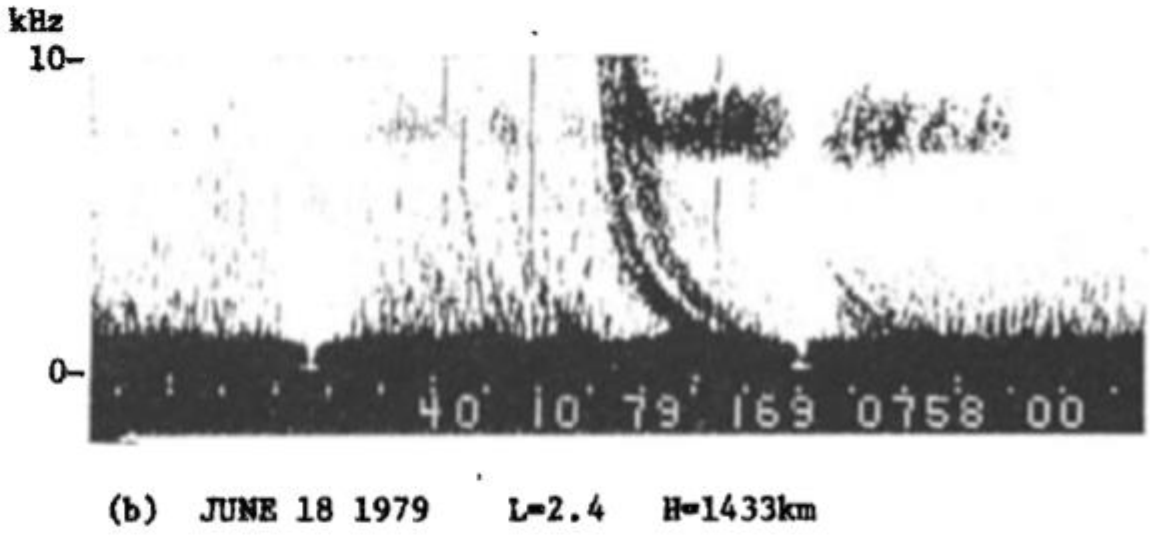
- Whistlers can interact with radiation belt electrons via gyro-resonance.
- Some of these electrons can precipitate onto the atmosphere/ionosphere.
- Precipitation can distort sub-ionospheric VLF signals.



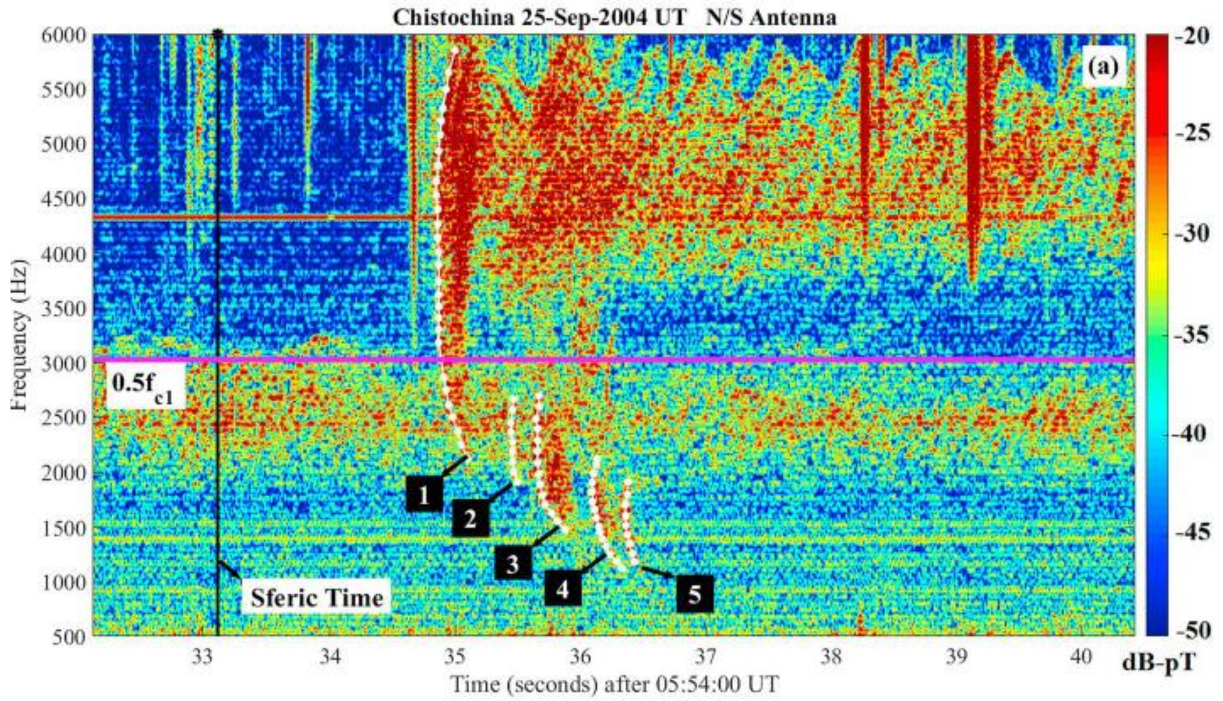
Whistlers: Triggering

- Whistlers can trigger free-running emissions and emissions that resemble upper-band chorus.

Nakamura and Ondoh, 1989



Hosseini et al., 2019



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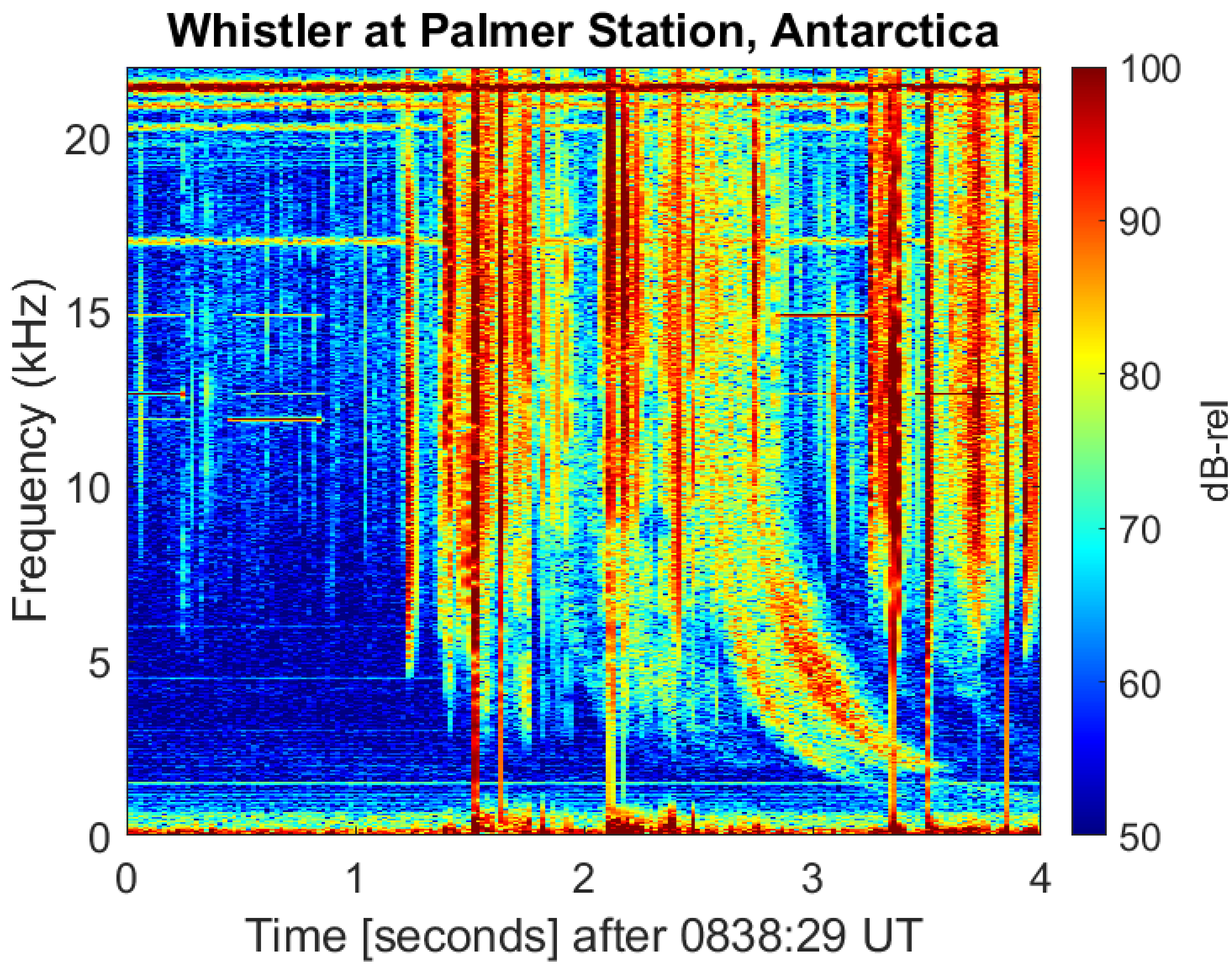
Detecting Whistlers

- Understanding whistler impacts is an important component space weather.
- Automated detection is required to gain a thorough statistical picture.
- Realistic data (especially ground-based data), is very noisy which makes automation difficult.



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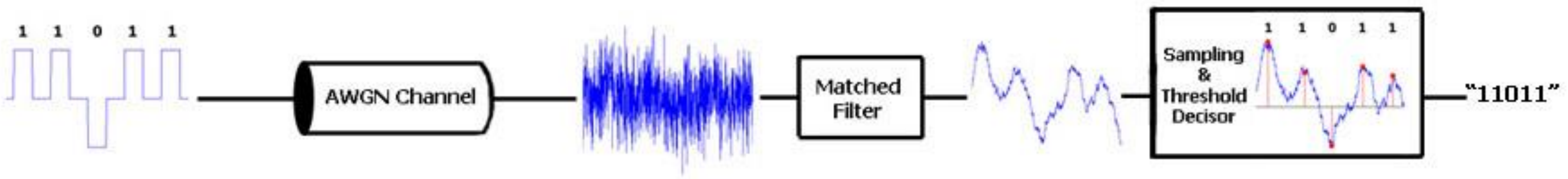
Traditional Signal Detection

- Traditional signal detection techniques utilize information about the signal’s structure (shape, duration, etc.).

- The most common method utilizes a cross-correlating with the expected signal. This is known as a matched filter.



By El pak at English Wikipedia - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=1874370

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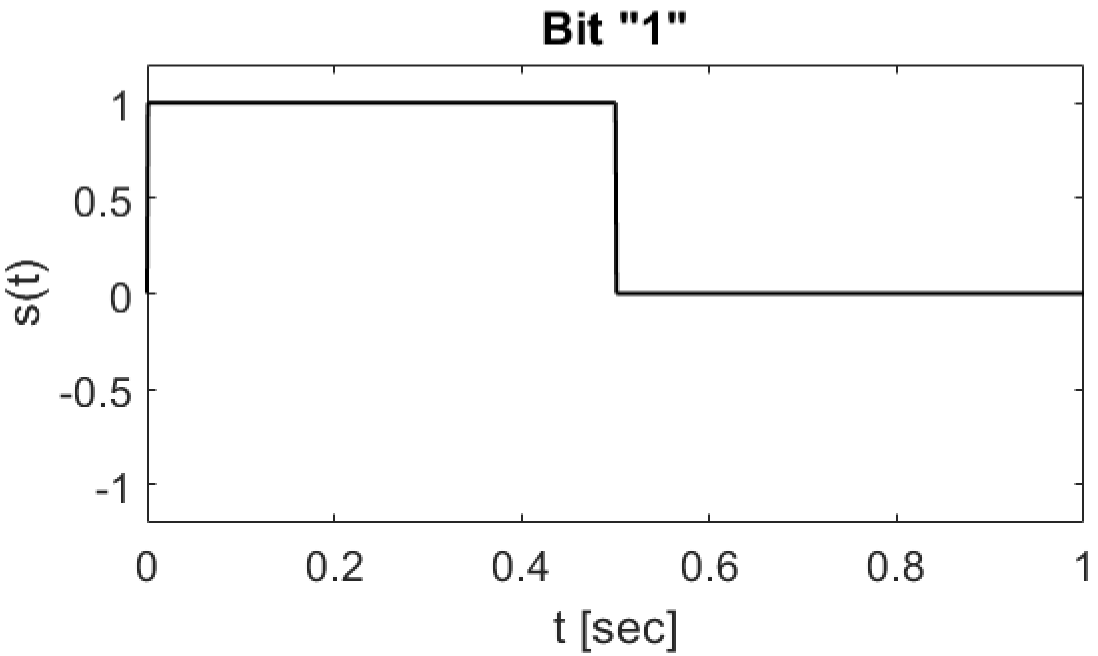
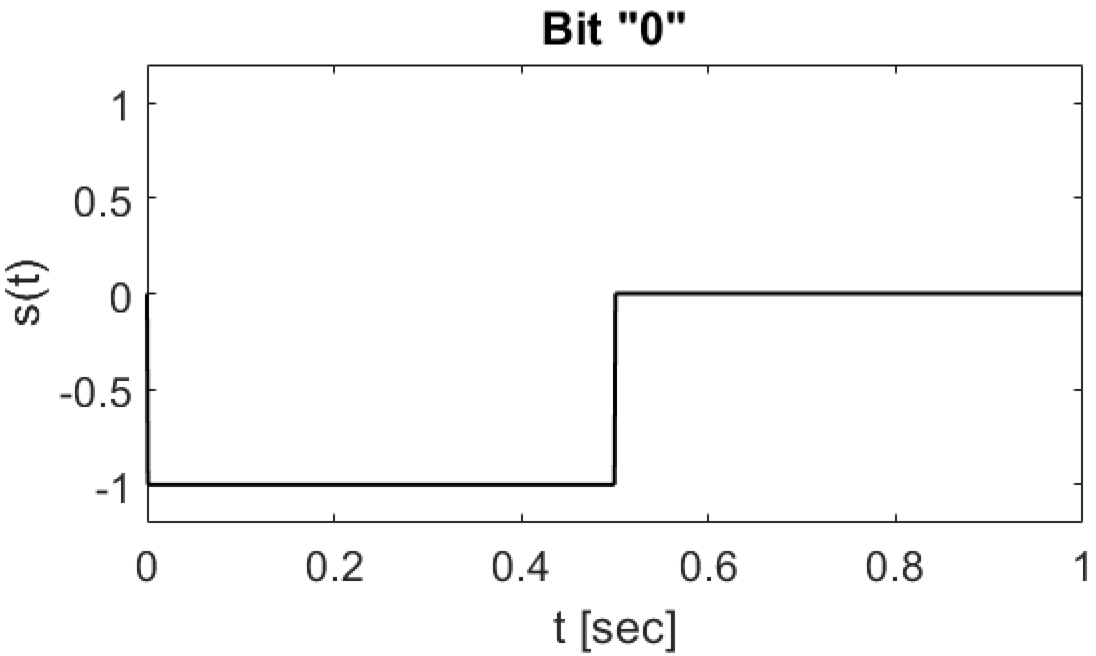
Example: Bit Stream Detection

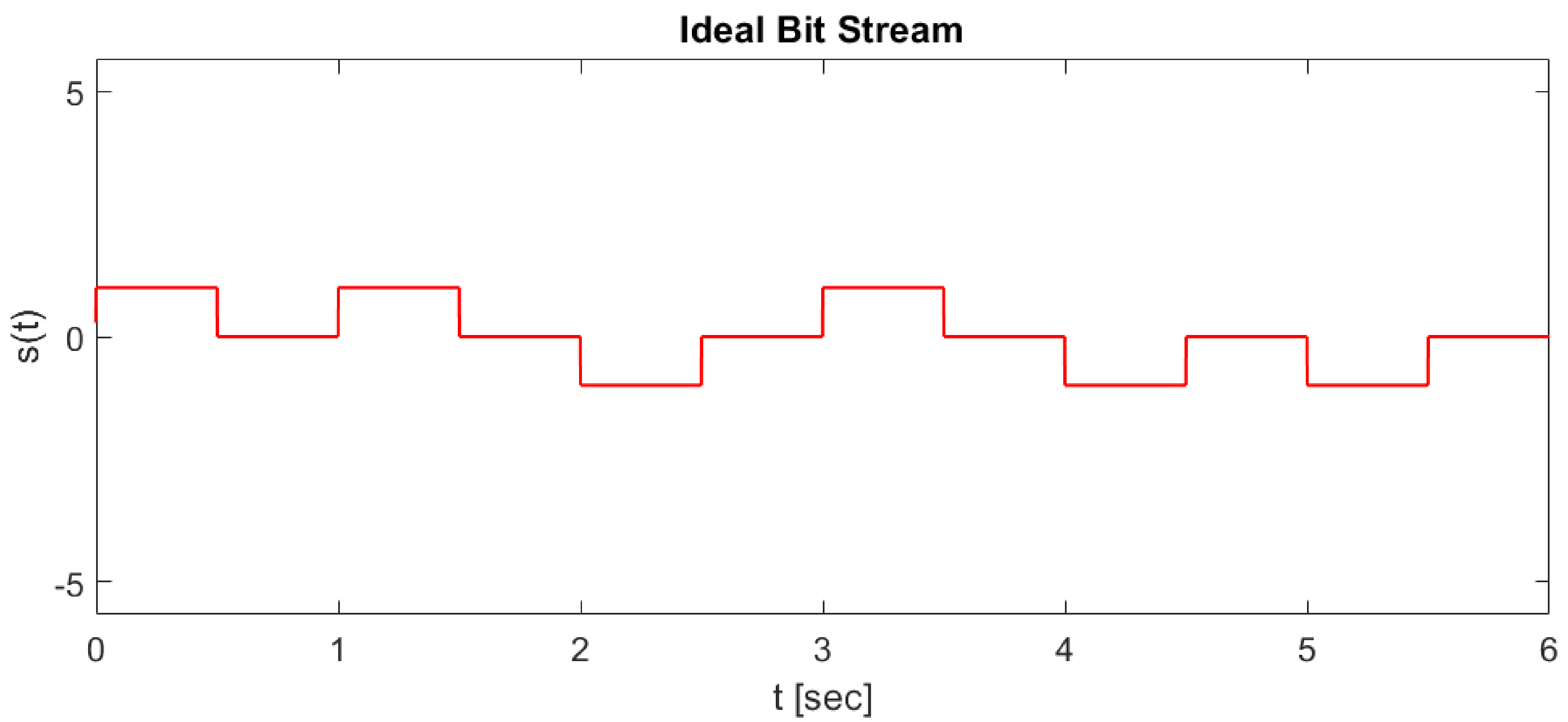
- Consider the case of detecting bits represented by rectangular pulses
- Examples of “1” and “0” are below:





Example: Bit Stream Detection

- More generally a bit stream can be represented by a sequence of 1s and 0s:



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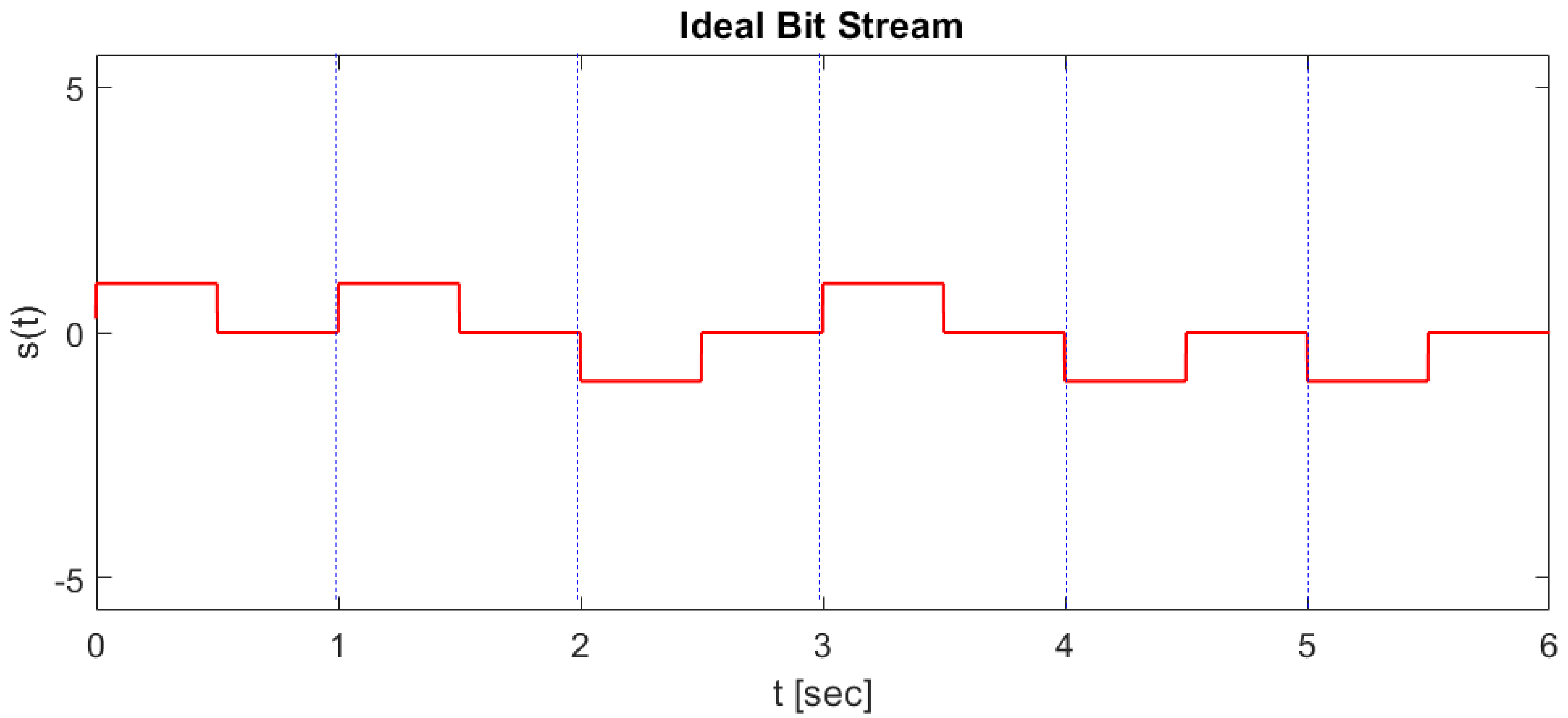

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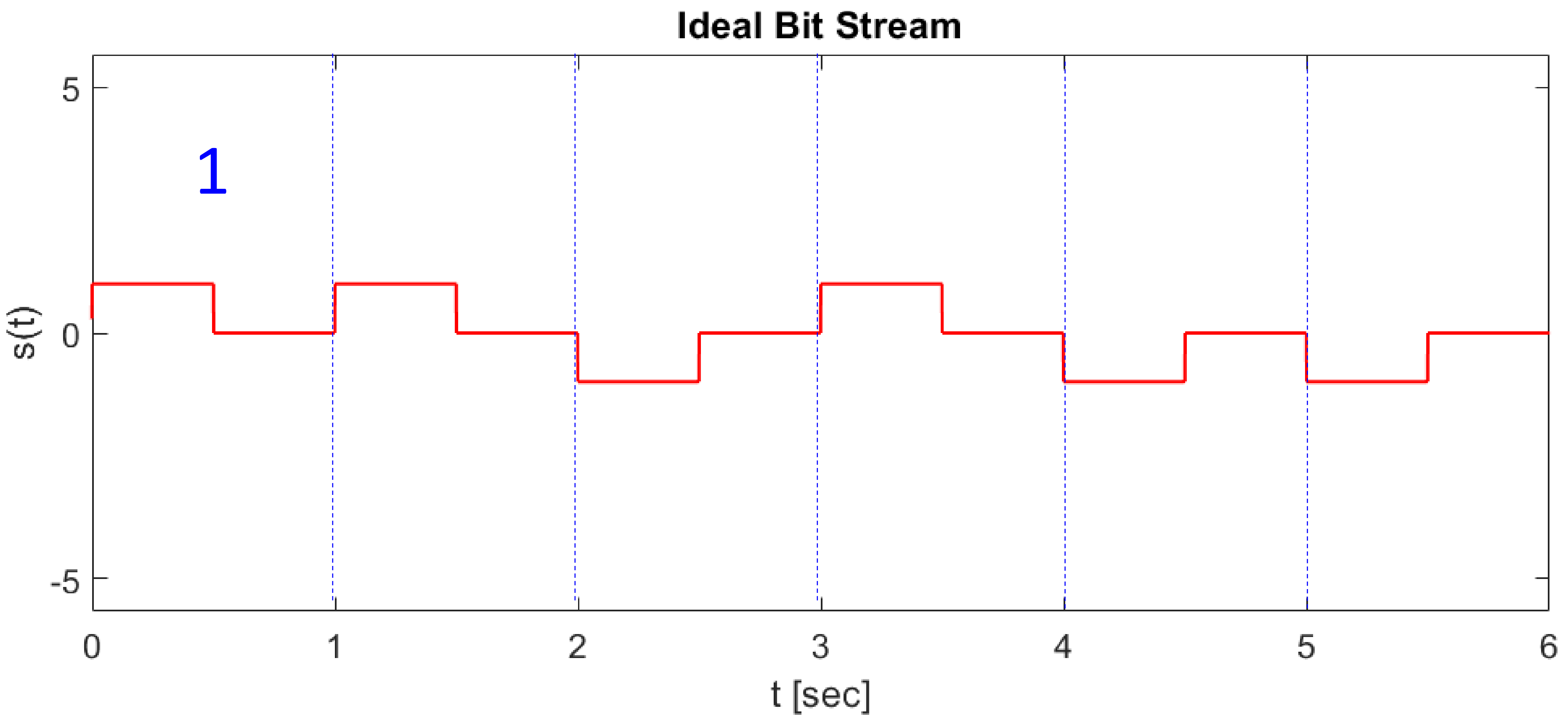

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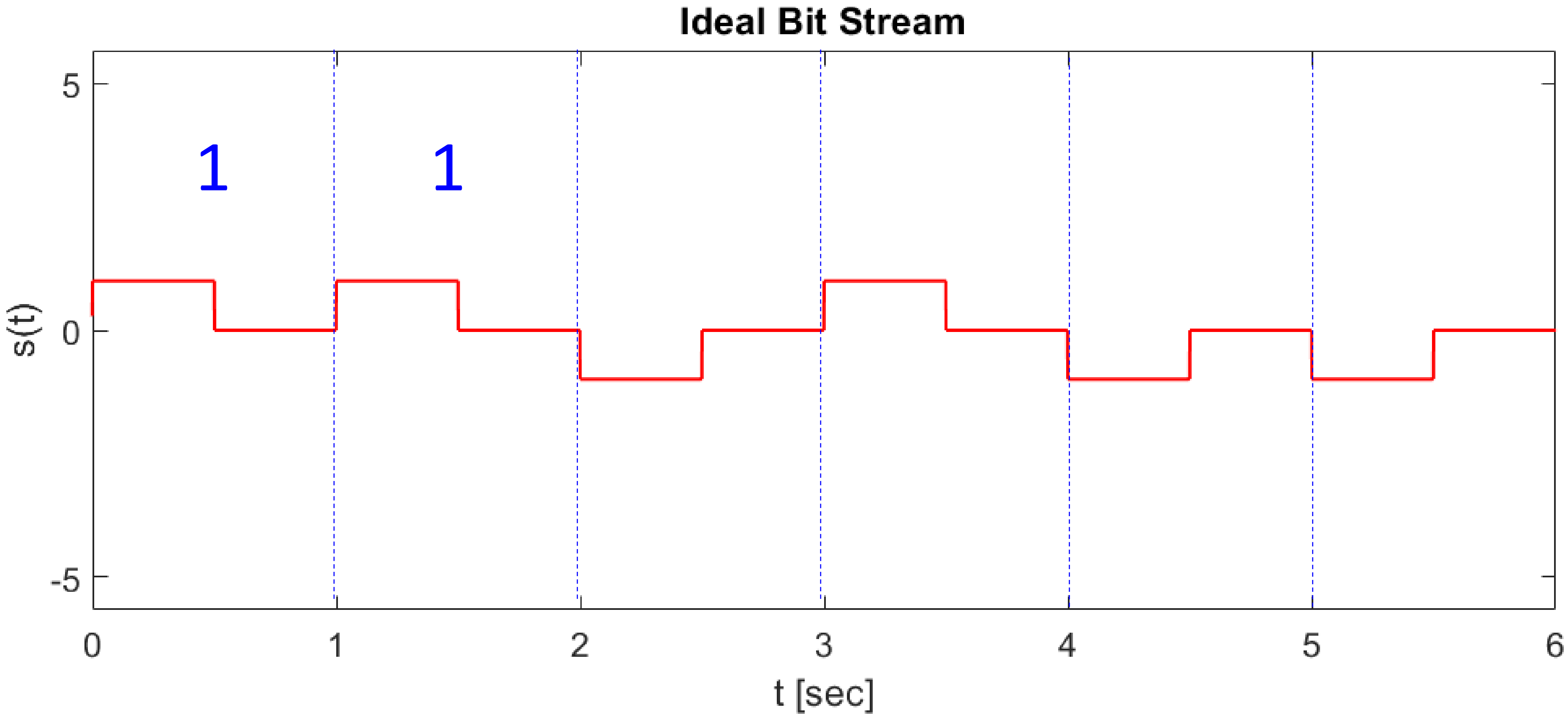

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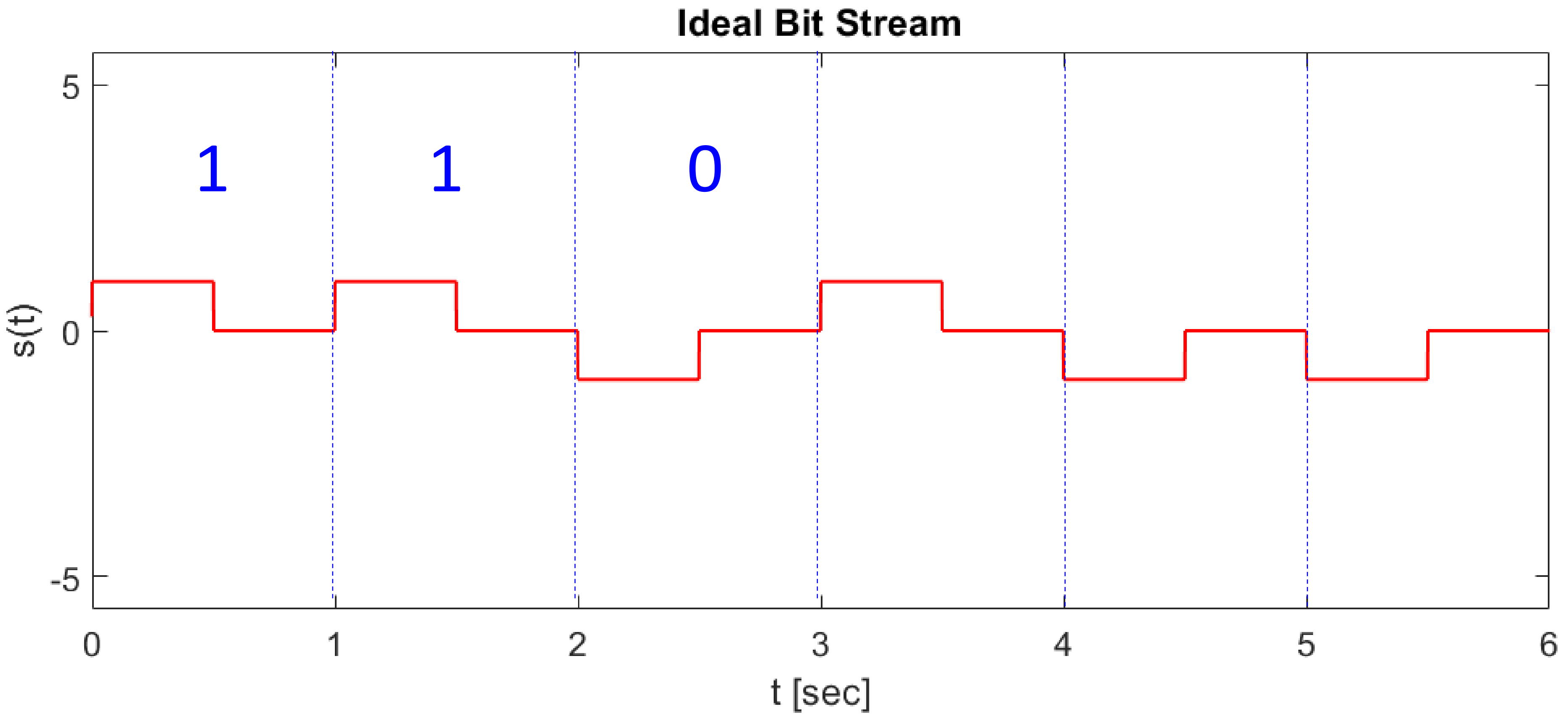

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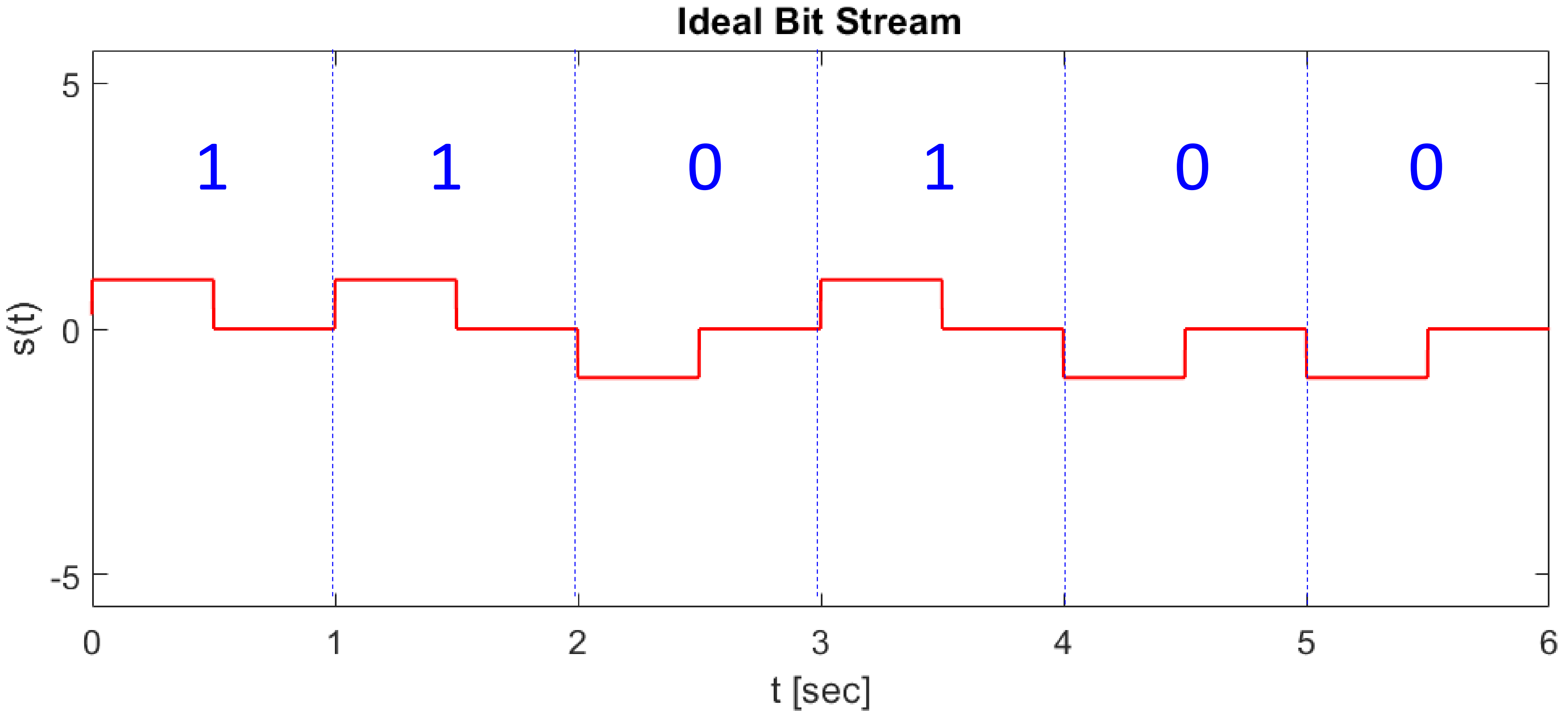
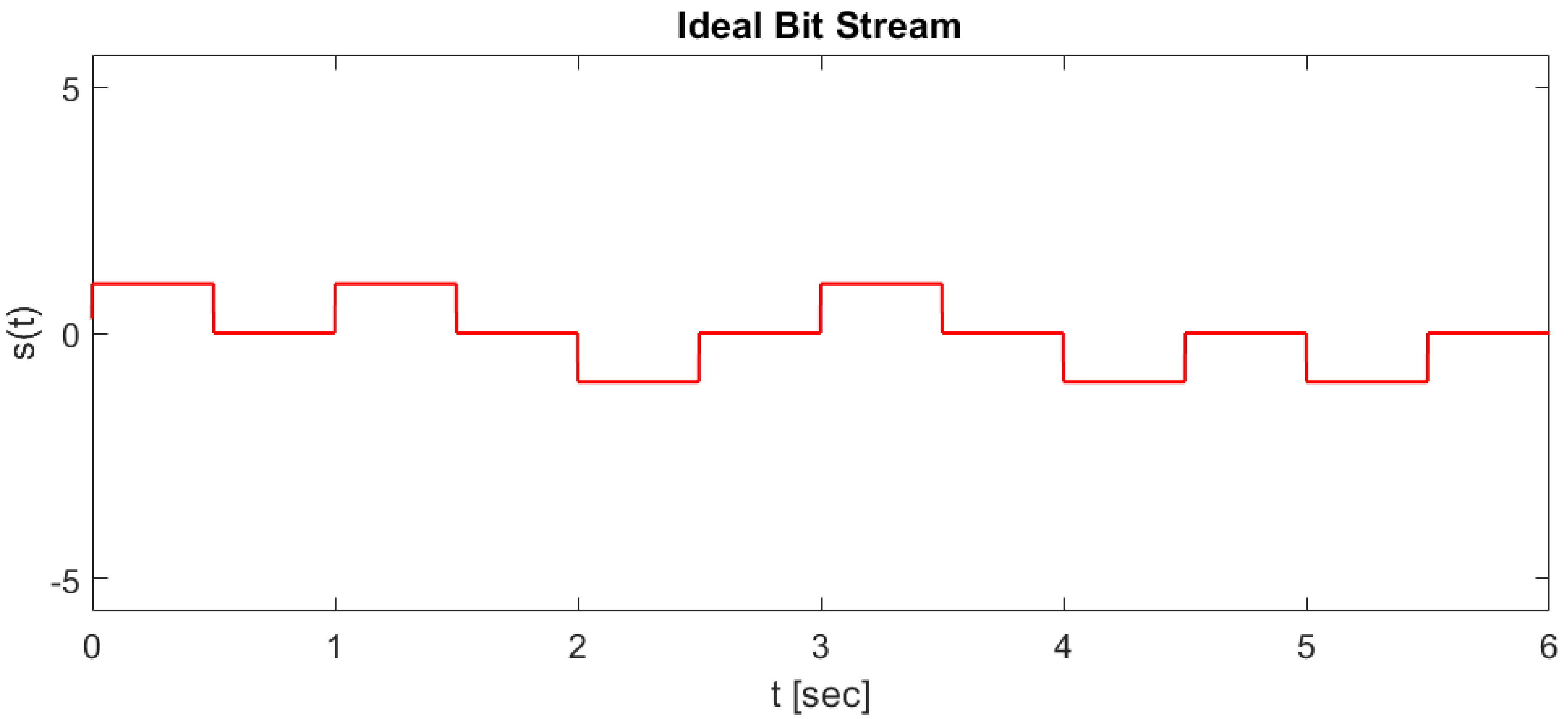


Example: Bit Stream Detection

- The individual bits can be detected using a matched filter (cross-correlation):



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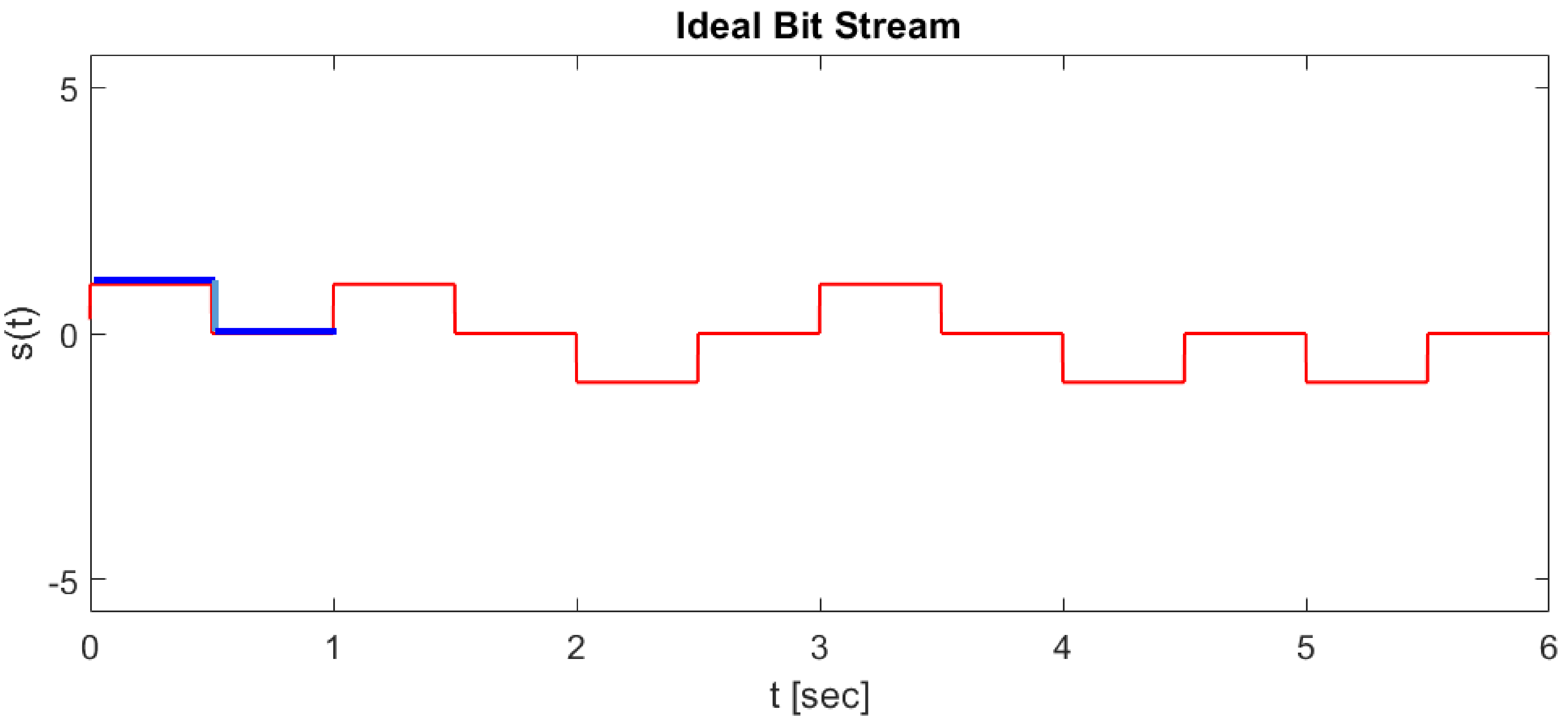

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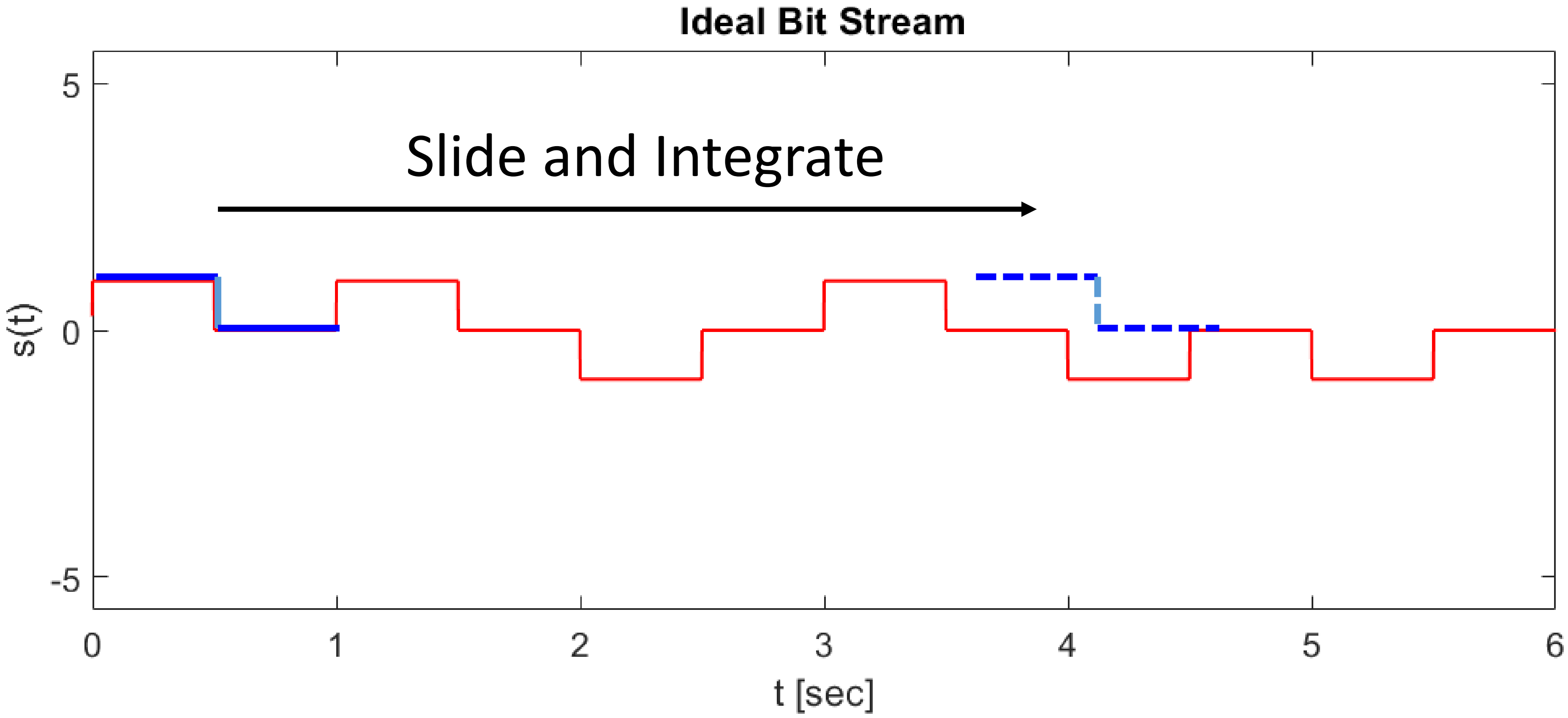
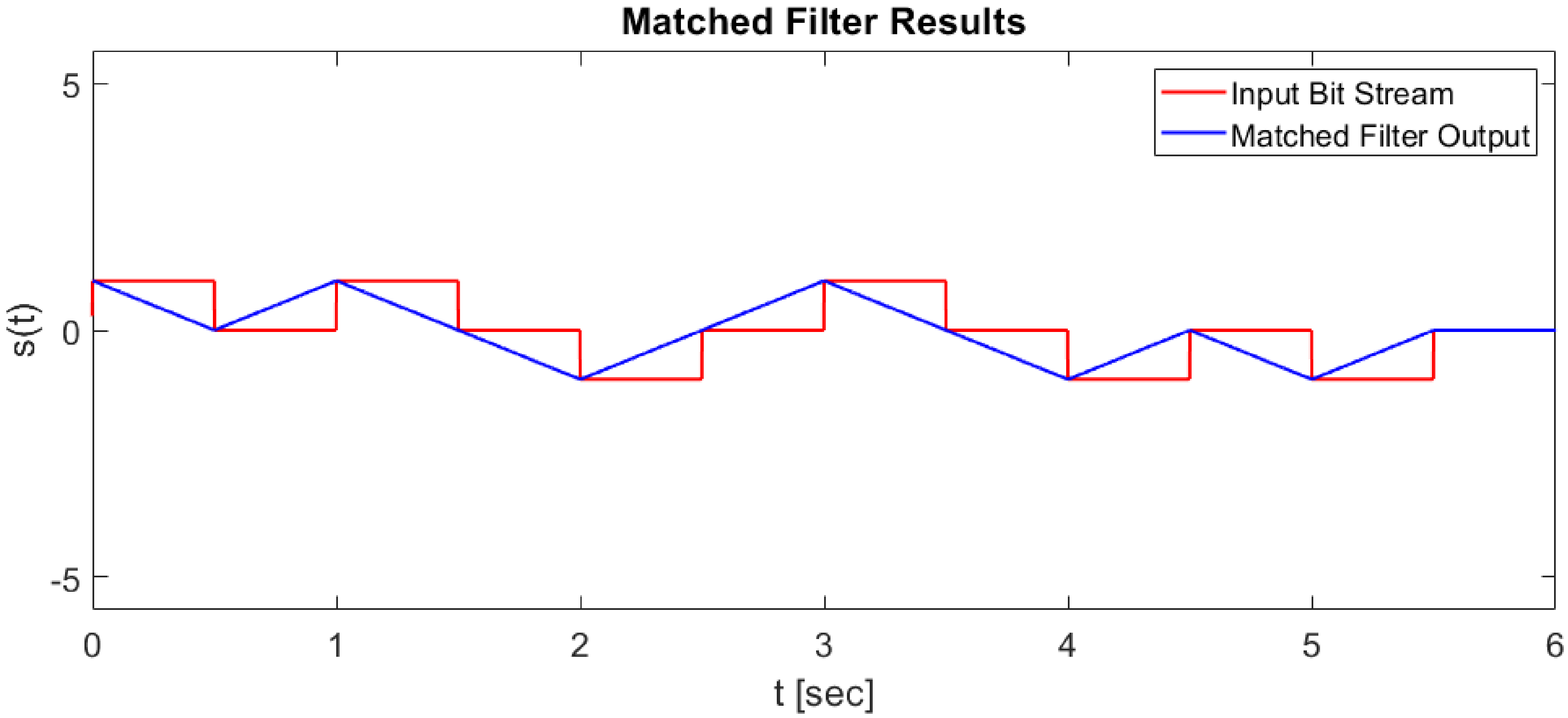


Example: Bit Stream Detection

- The output of the matched filter has positive peaks for “1” and negative peaks for “0”.



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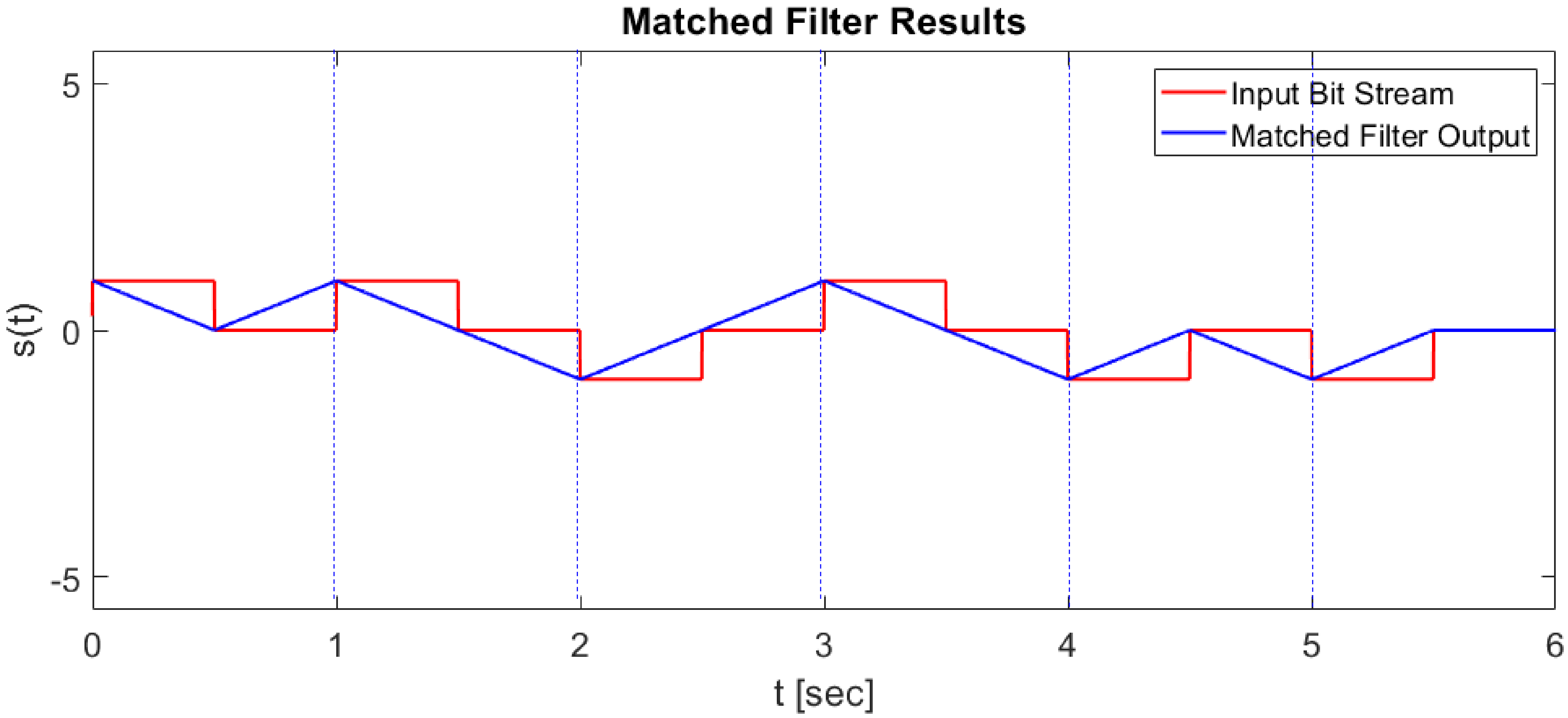

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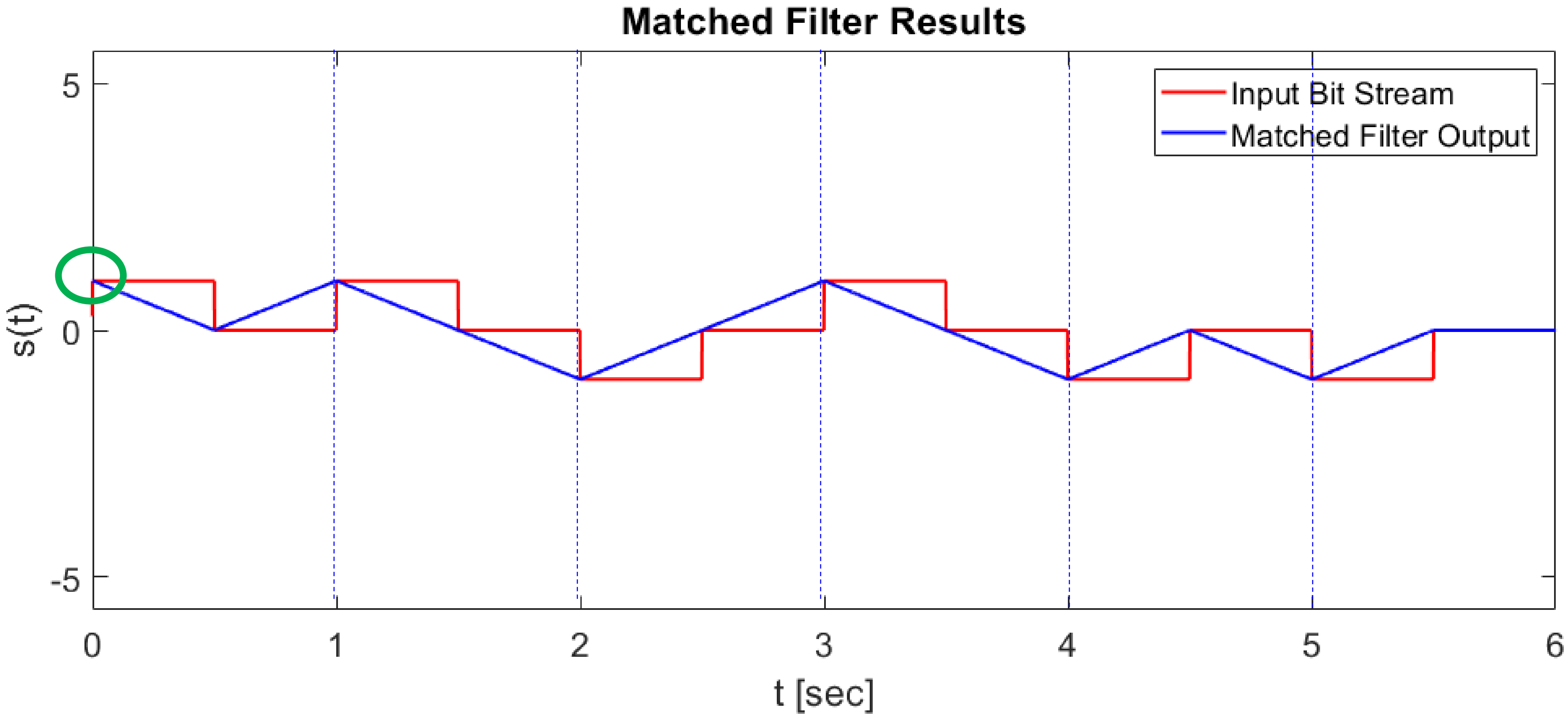

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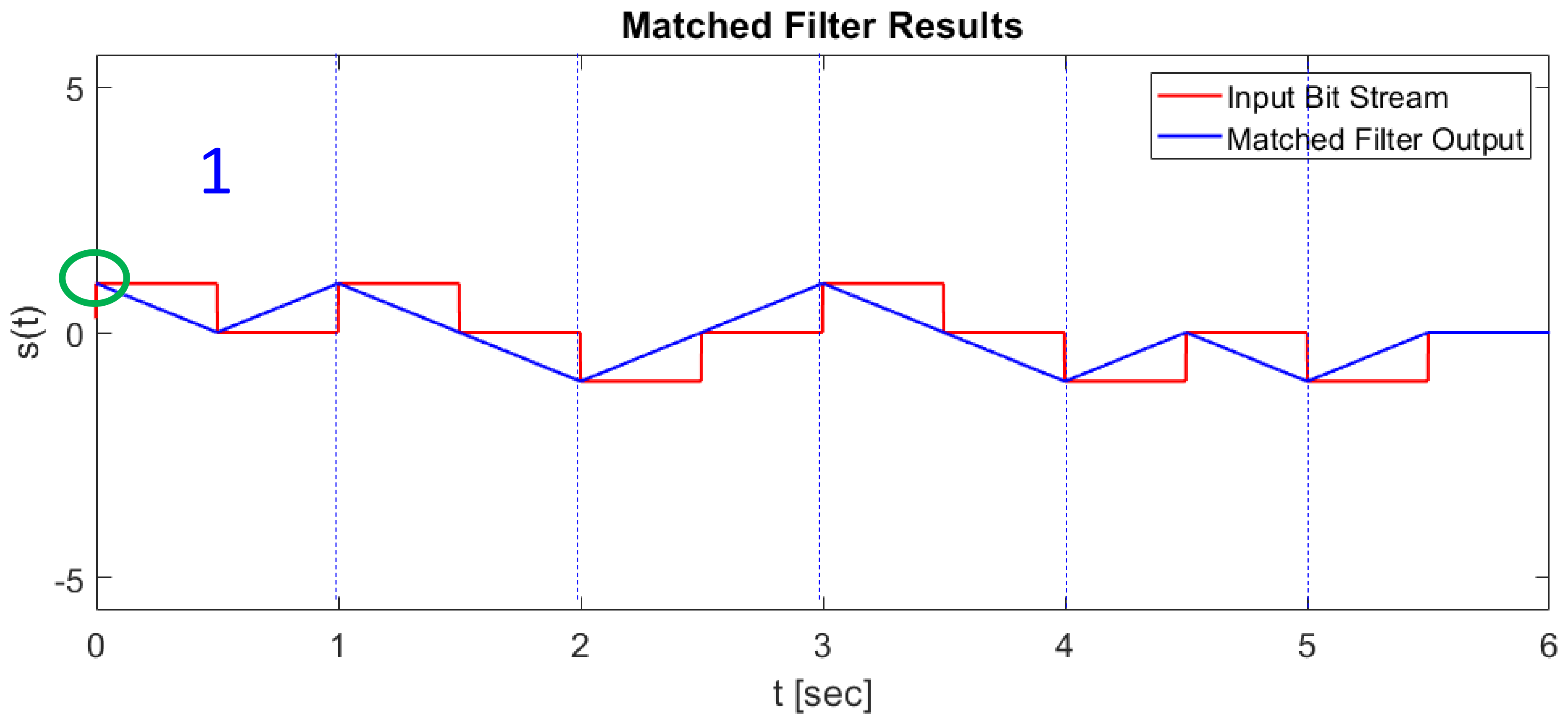

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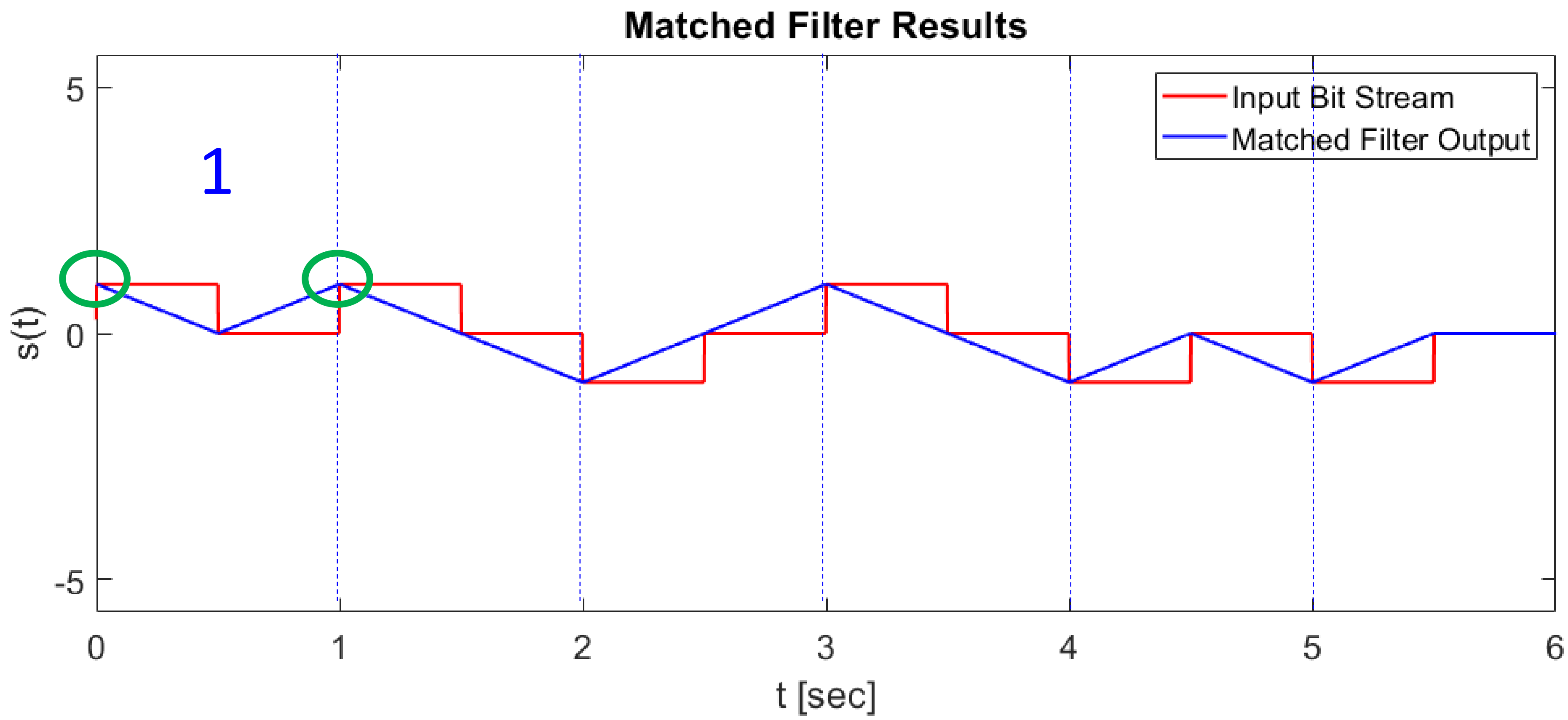

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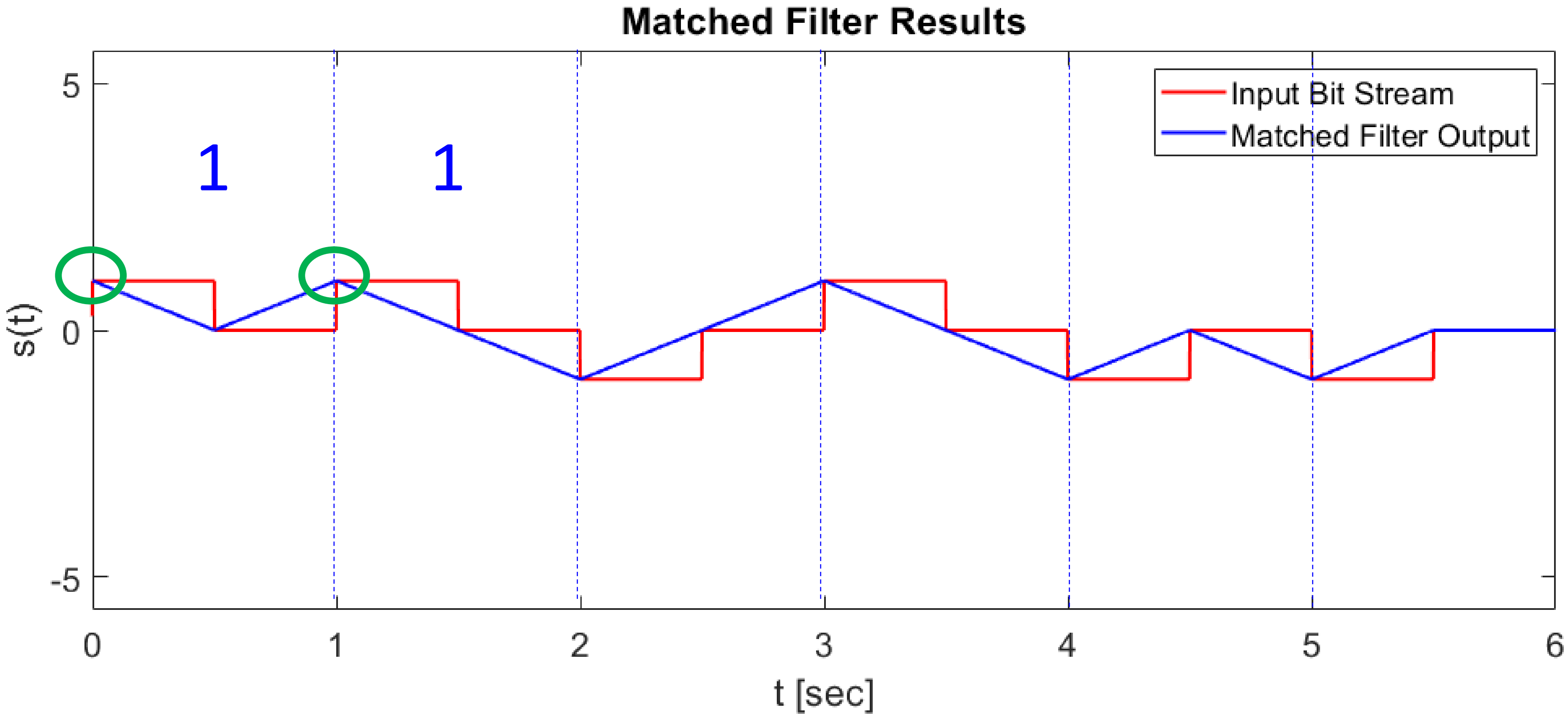

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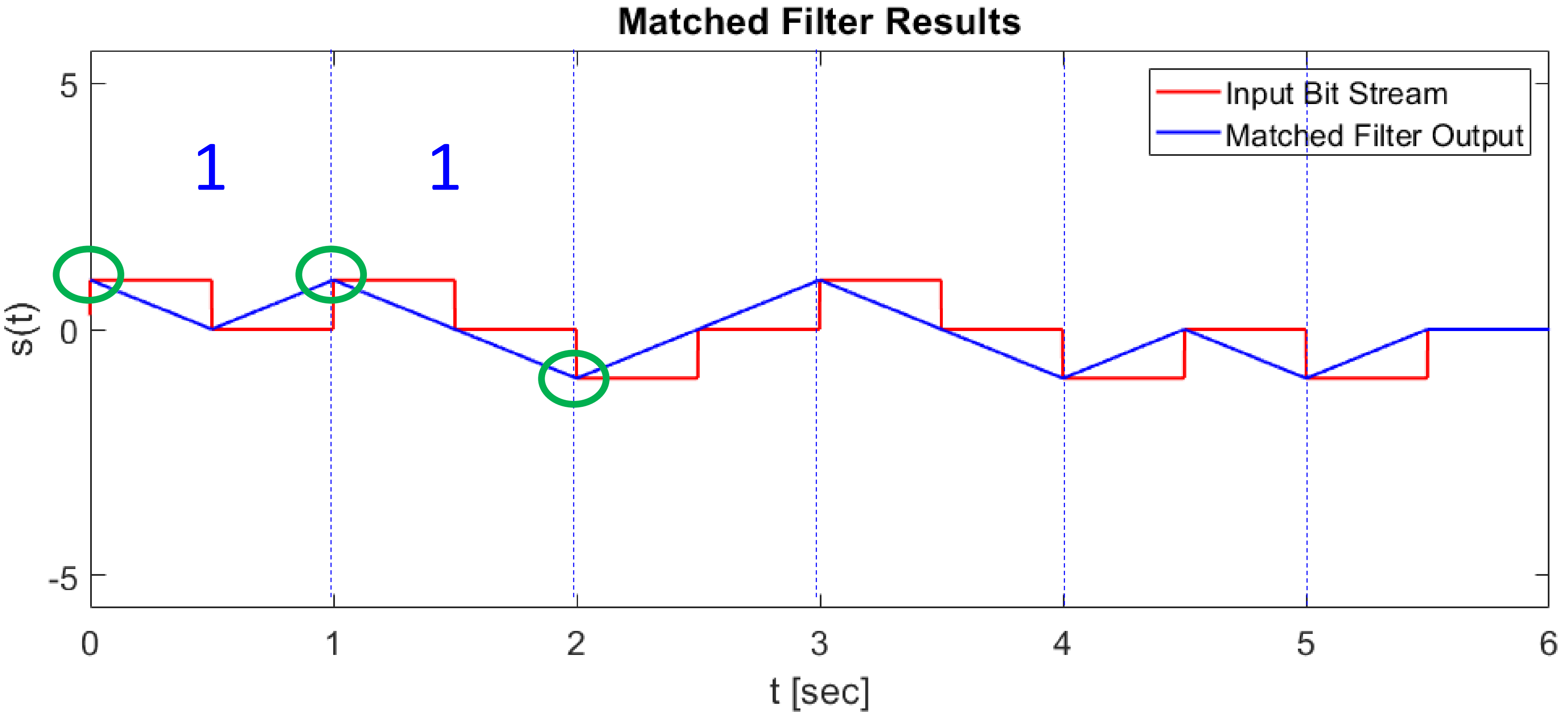

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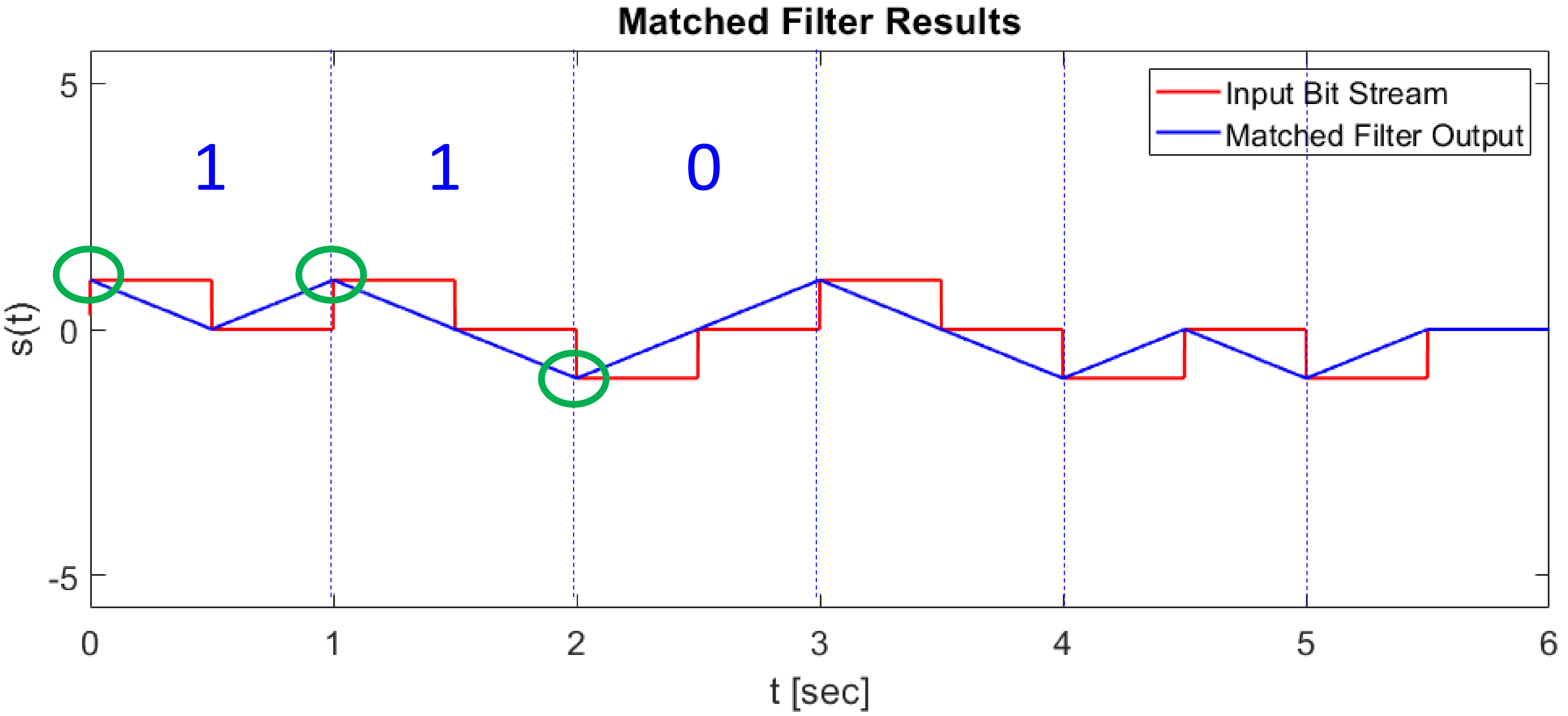

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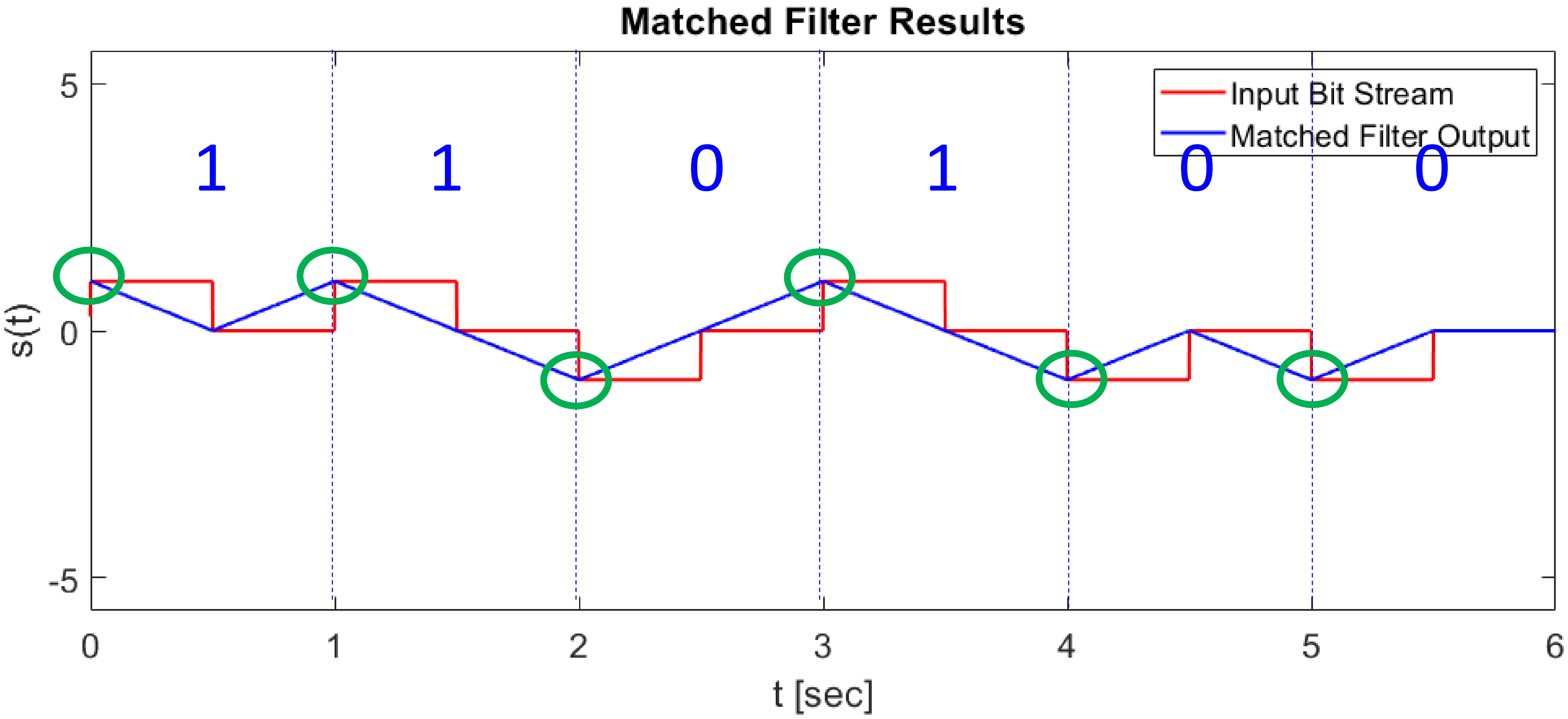
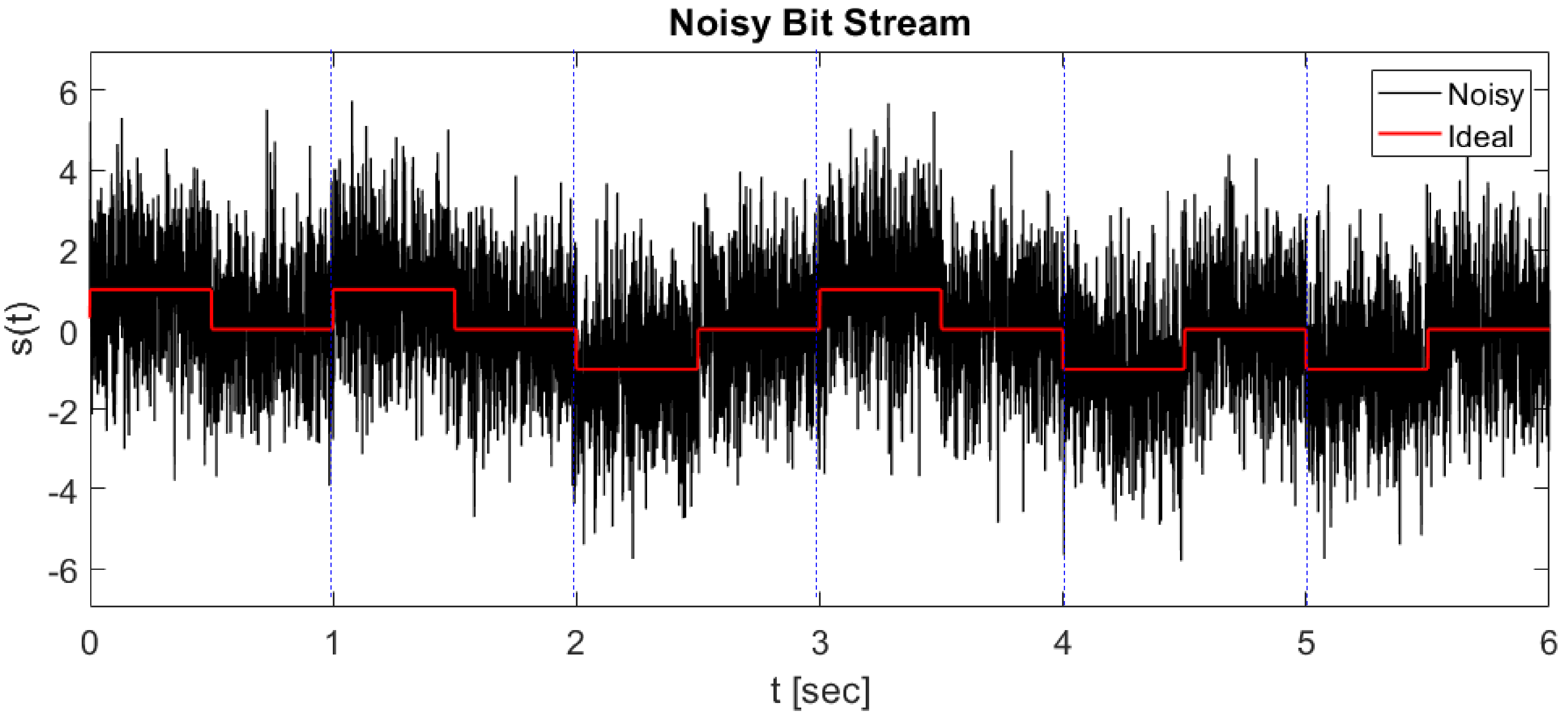


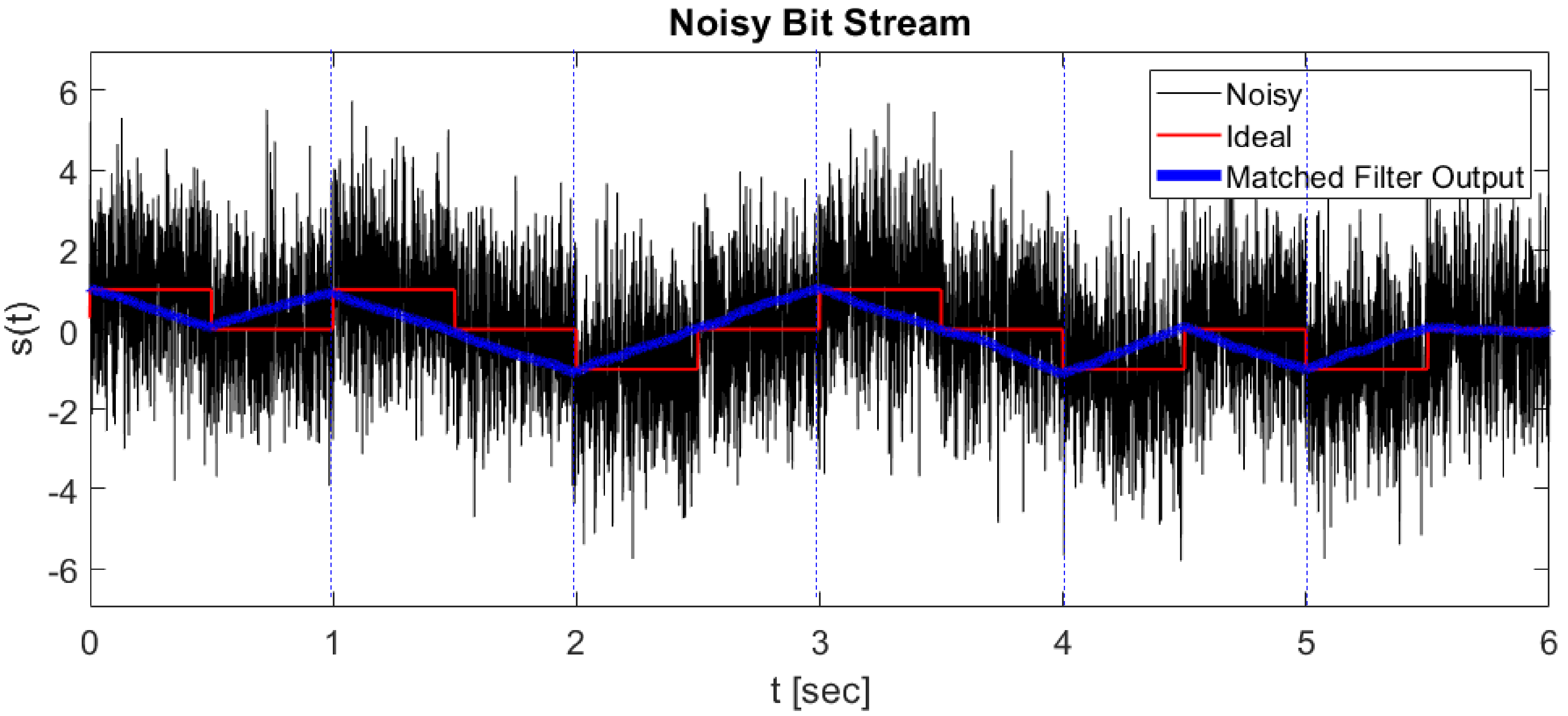
Example: Noisy Bit Stream Detection

- In practice, realistic signals are received in a noisy environment:



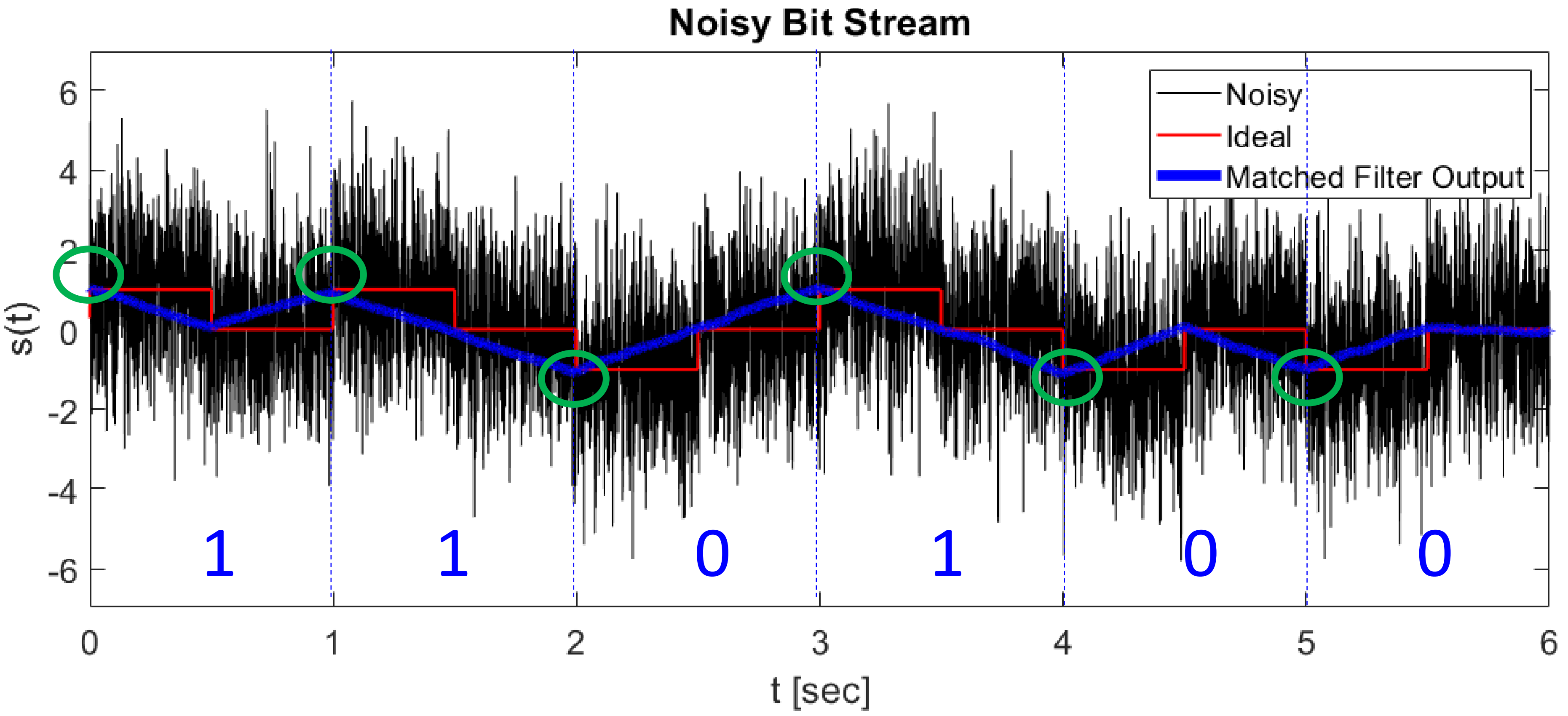
Example: Noisy Bit Stream Detection

- The matched filter output is almost the same as the for noise-free environment!



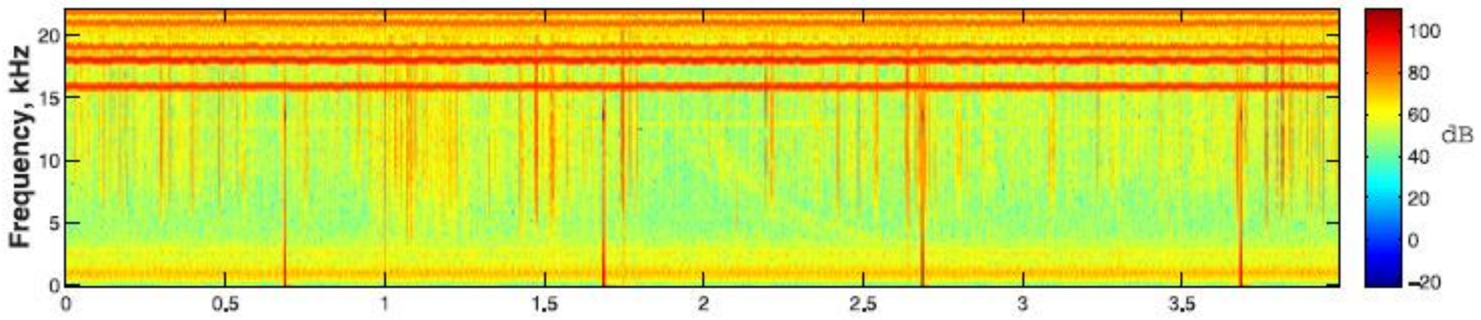
Example: Noisy Bit Stream Detection

- The matched filter technique works extremely well in a noisy environment!



Extension to Whistler Detection

This type of "template matching" technique has been quite successful when applied to detecting whistlers (see *Lichtenberger et al. 2008*):



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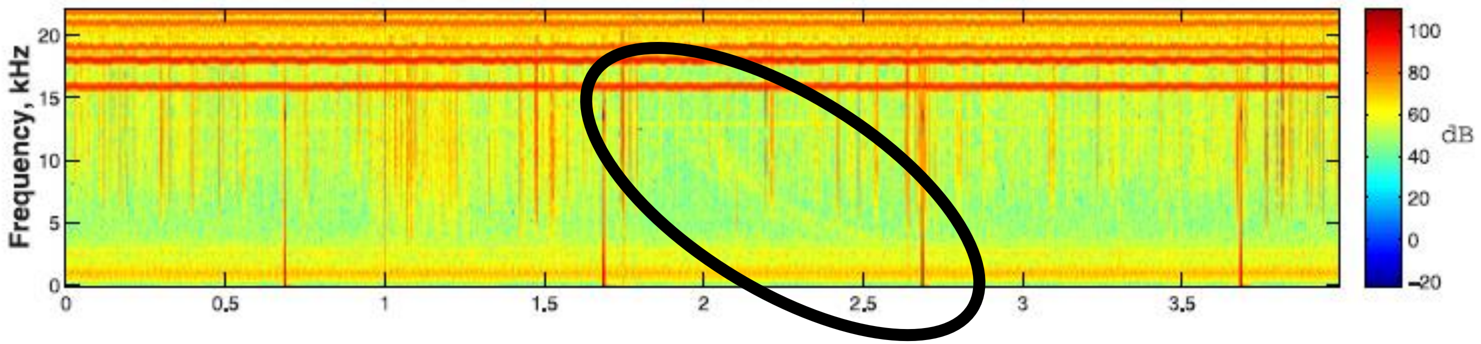

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Whistler Template

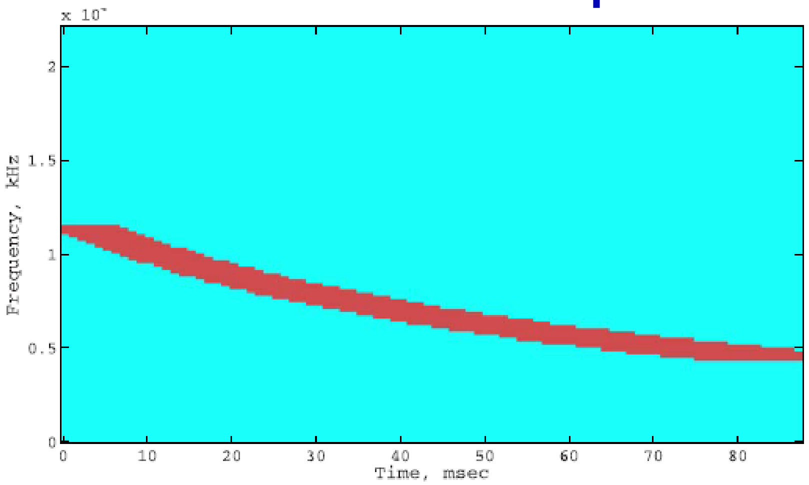
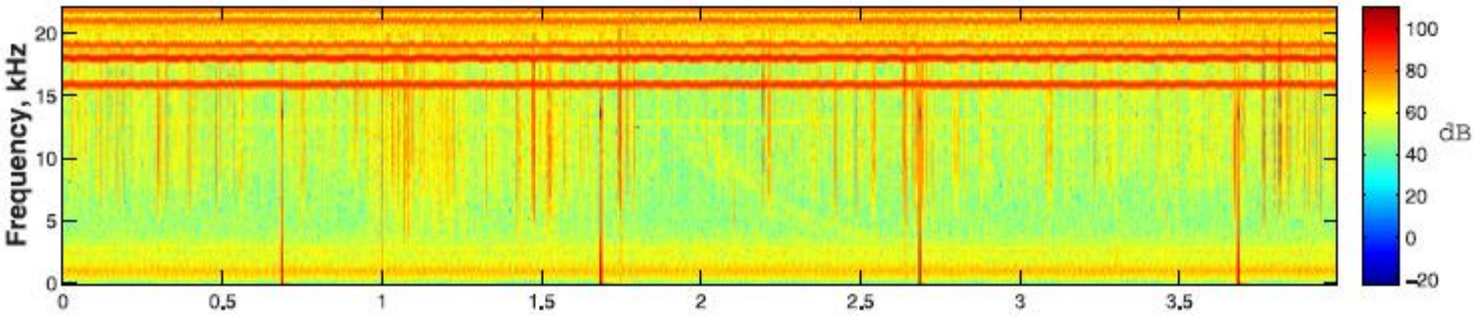


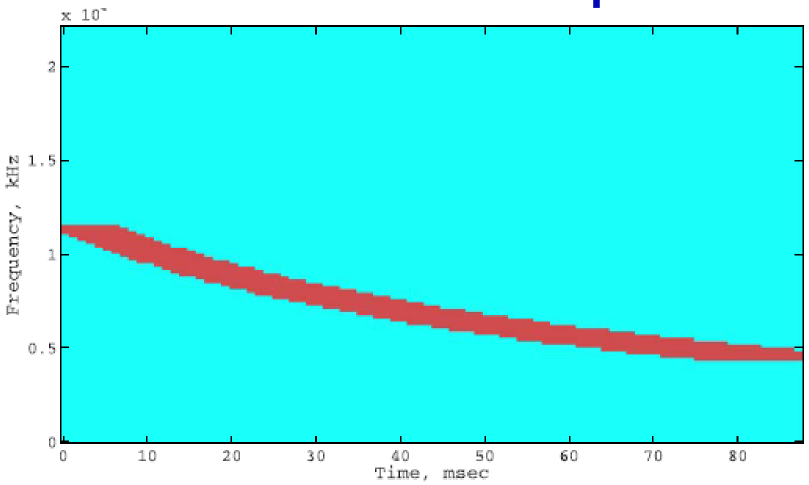
Figure 3. Multidispersion detector pattern.



Extension to Whistler Detection

This type of "template matching" technique has been quite successful when applied to detecting whistlers (see *Lichtenberger et al. 2008*):

Whistler Template



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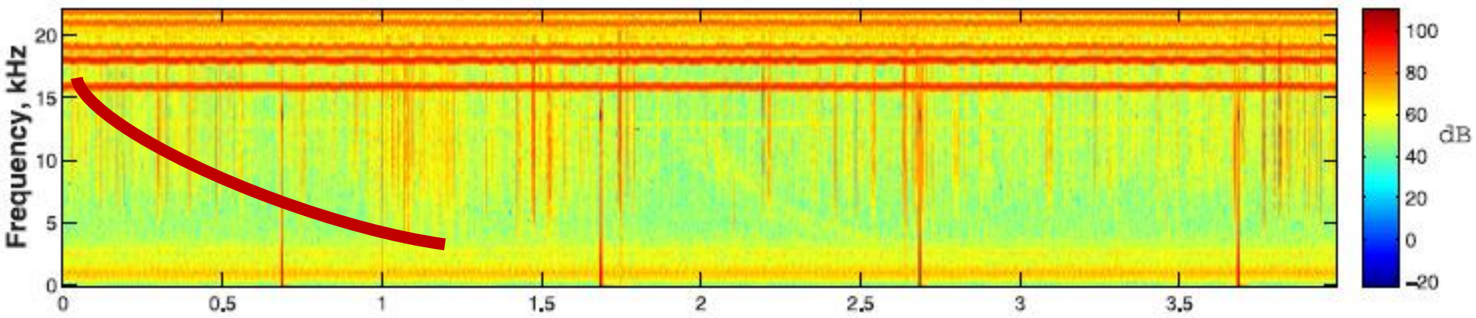

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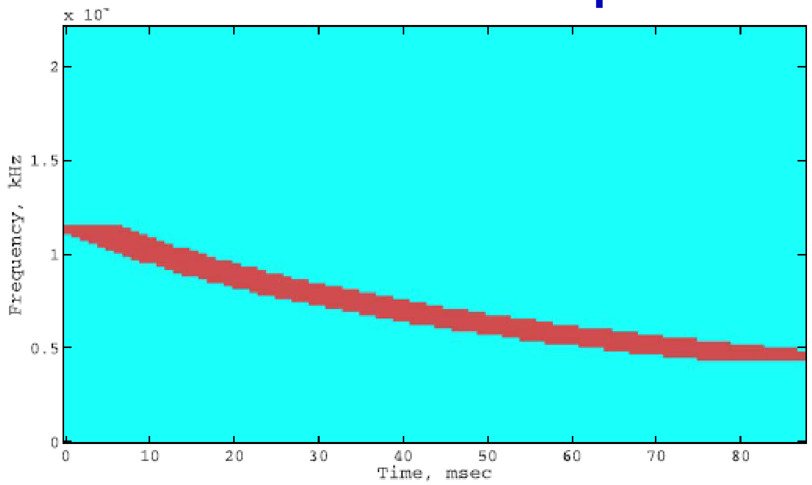

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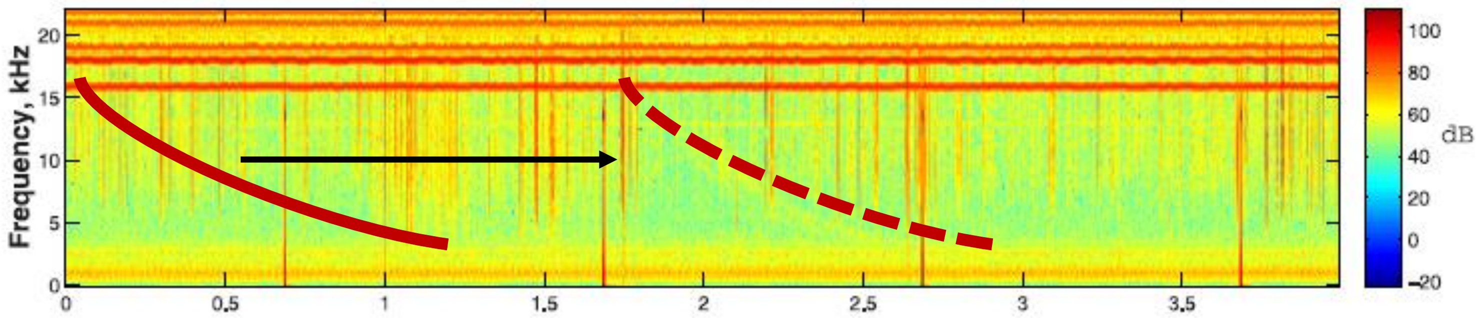

Extension to Whistler Detection

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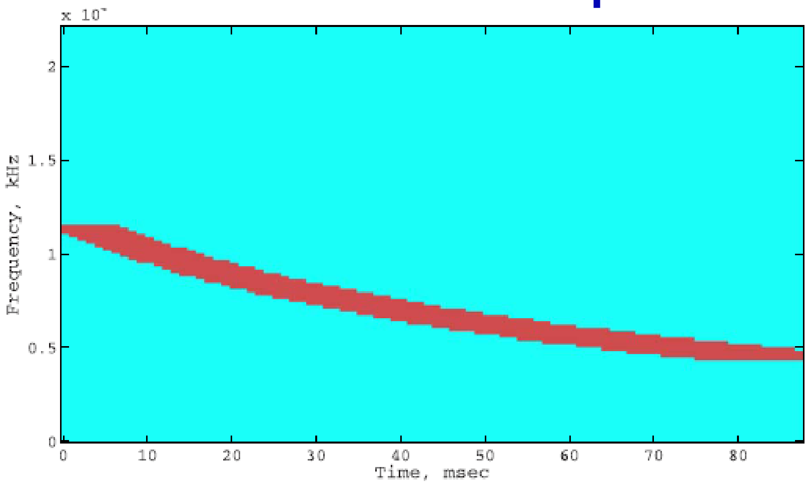

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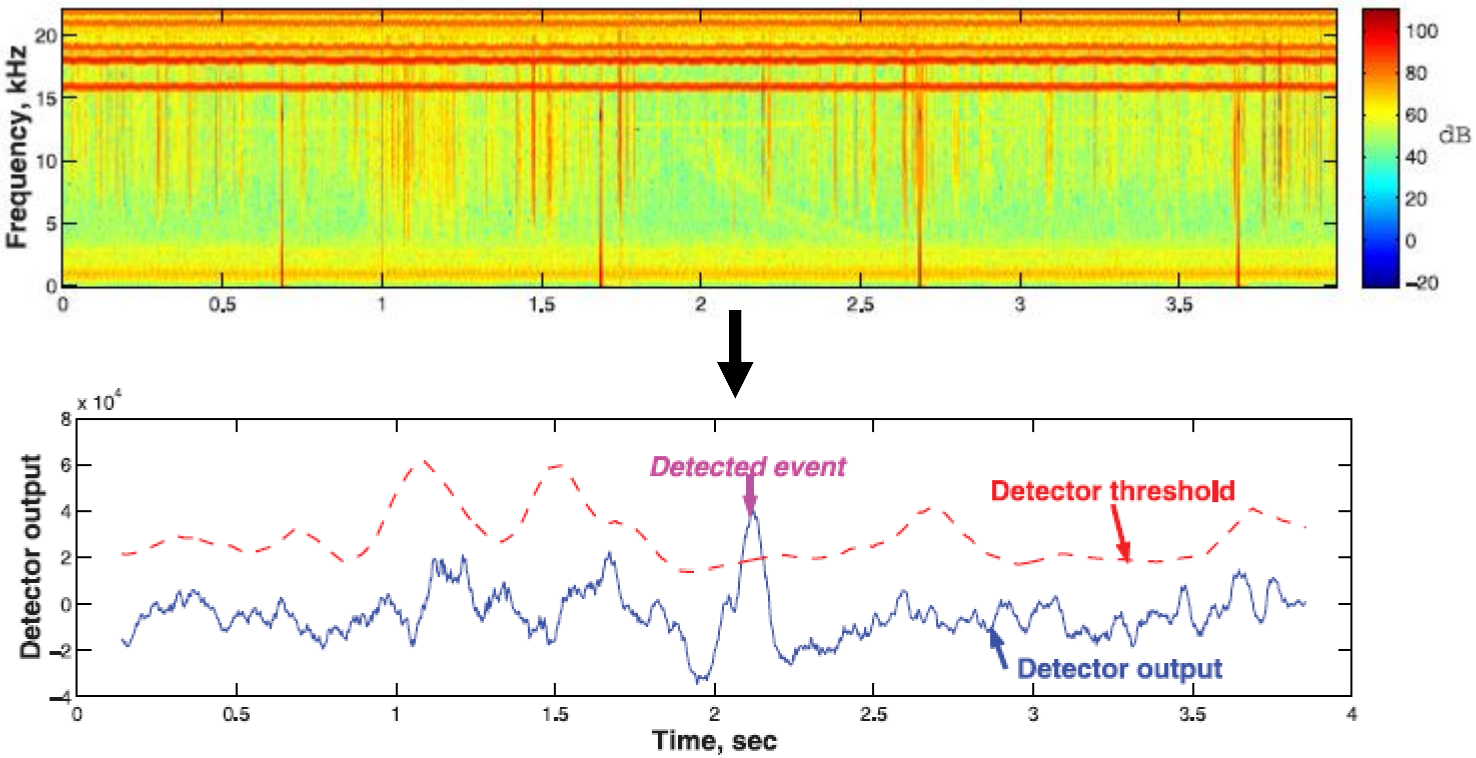
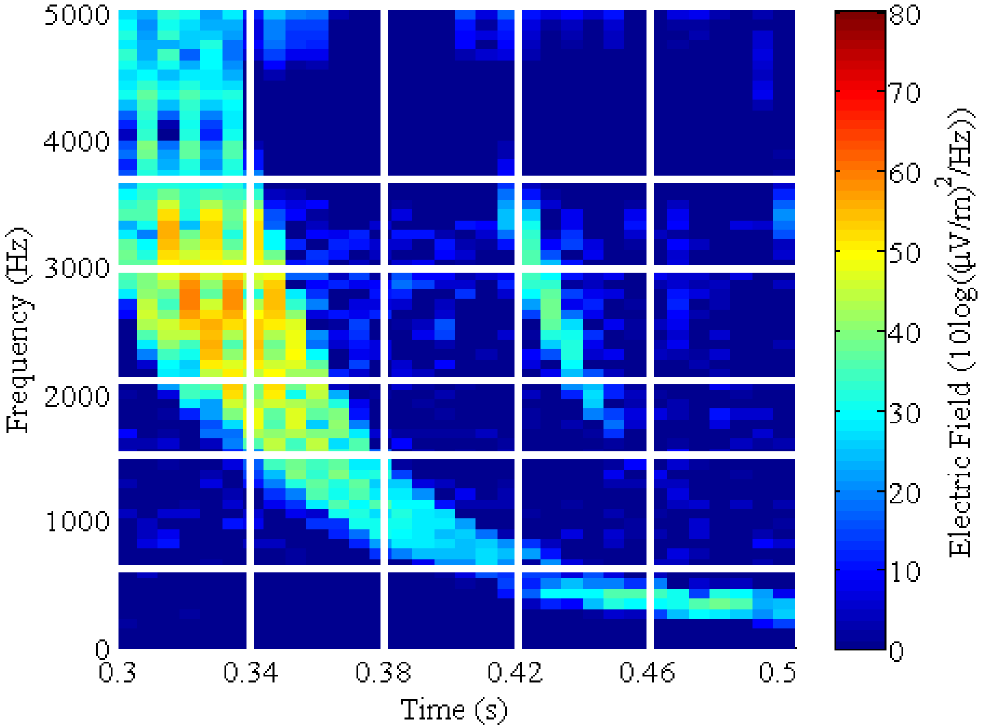


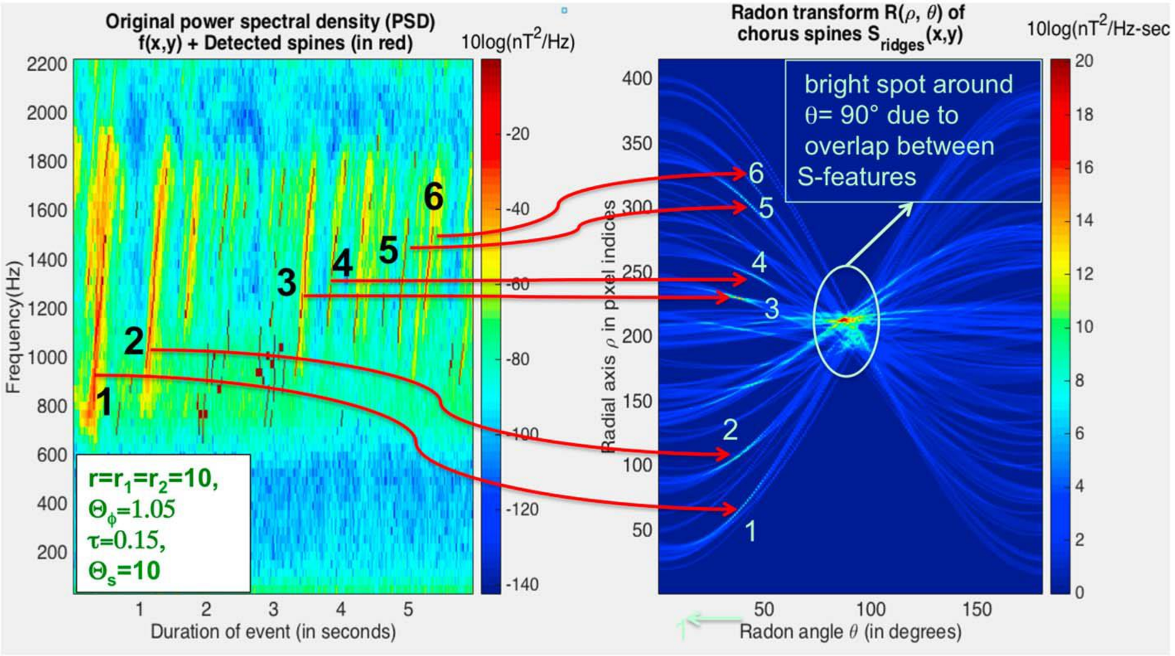
Traditional Signal Extraction Methods

Modified versions of this technique have been successful when applied to detecting various types of whistler-mode waves…they all require explicit knowledge of the signal structure!

Compston, 2016



Gupta et al., 2021



(a) (b)

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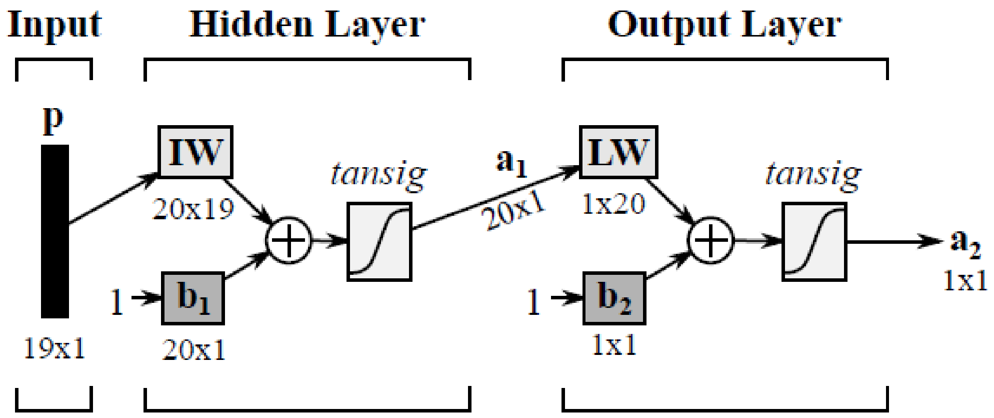
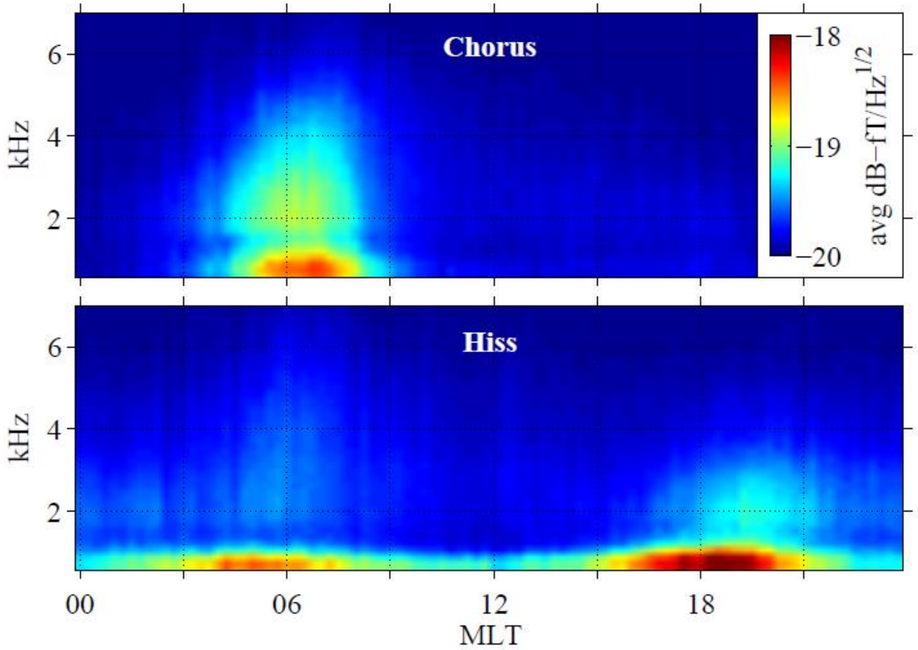
Machine Learning Methods

- We now have thousands of events of waves relevant to the space environment.
- Large datasets permit the use of data-driven models.
- Machine learning approaches are becoming very useful for detecting/extracting signals from the space environment.





Golden 2011

Outline

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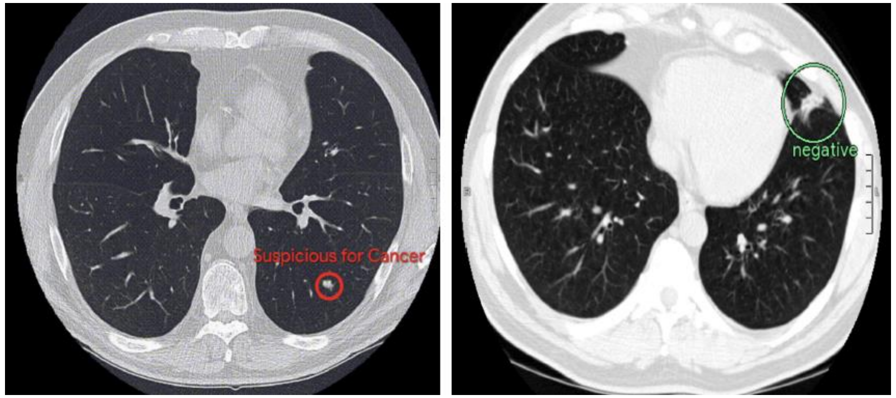
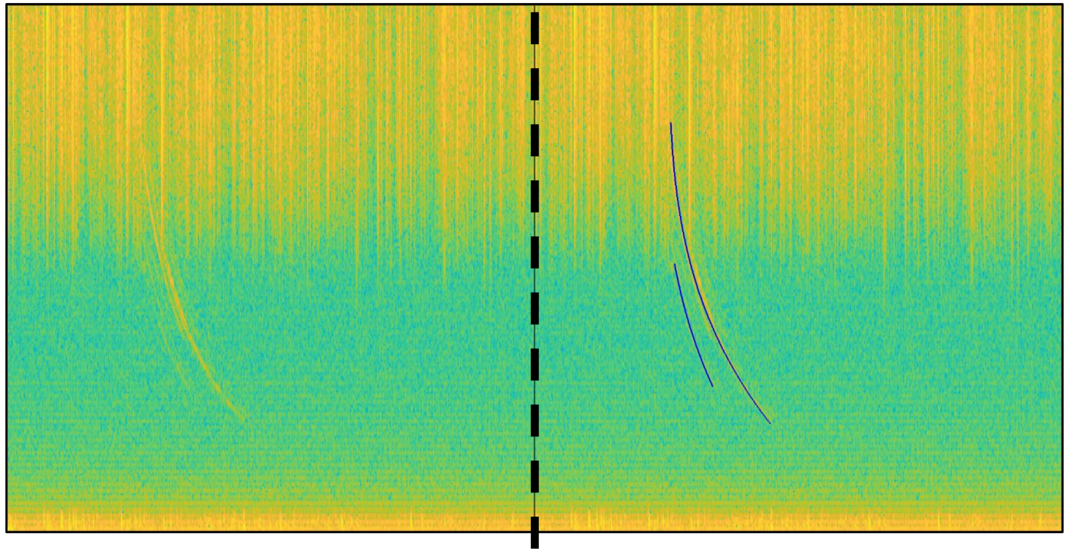
2. Traditional Methods of Signal Detection
3. Basic Overview of Neural Networks
4. Whistler Extraction using MSRCNN
5. Summary and Future Work

Machine Learning Applications

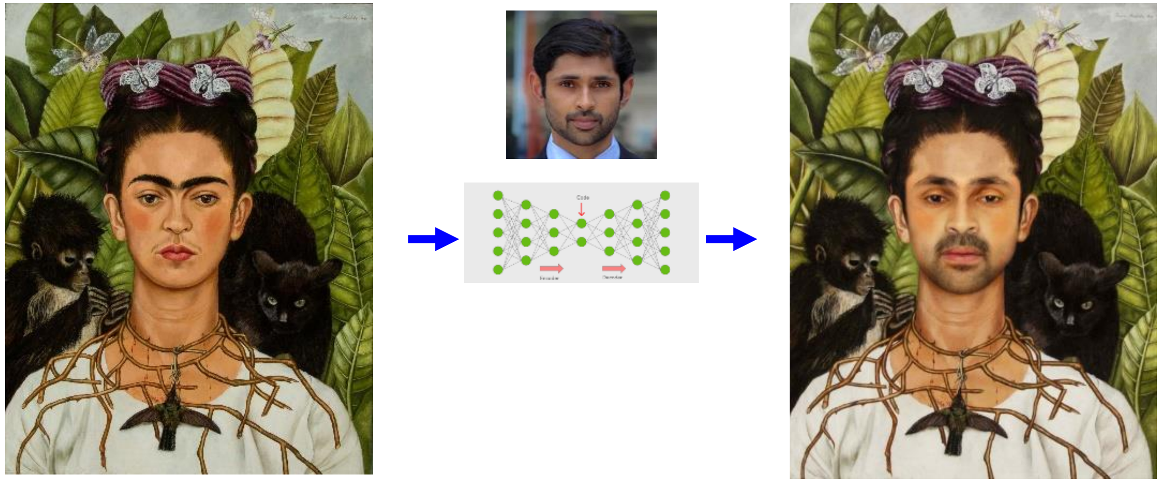


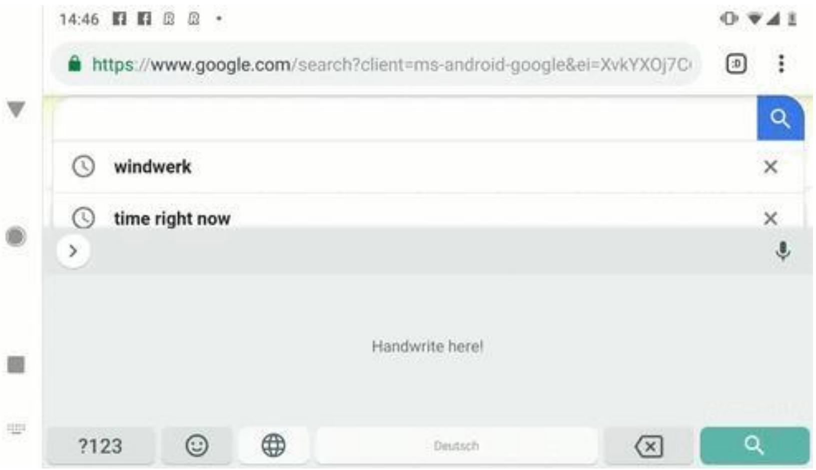
https://venturebeat.com/2019/05/20/googles-lung-cancer-detection-ai-outperforms-6-human-radiologists/

Original Spectrogram | **Extracted Whistlers**



Harid et al., 2021 (GRL)





https://ai.googleblog.com/2019/03/rnn-based-handwriting-recognition-in.html

Machine Learning Applications

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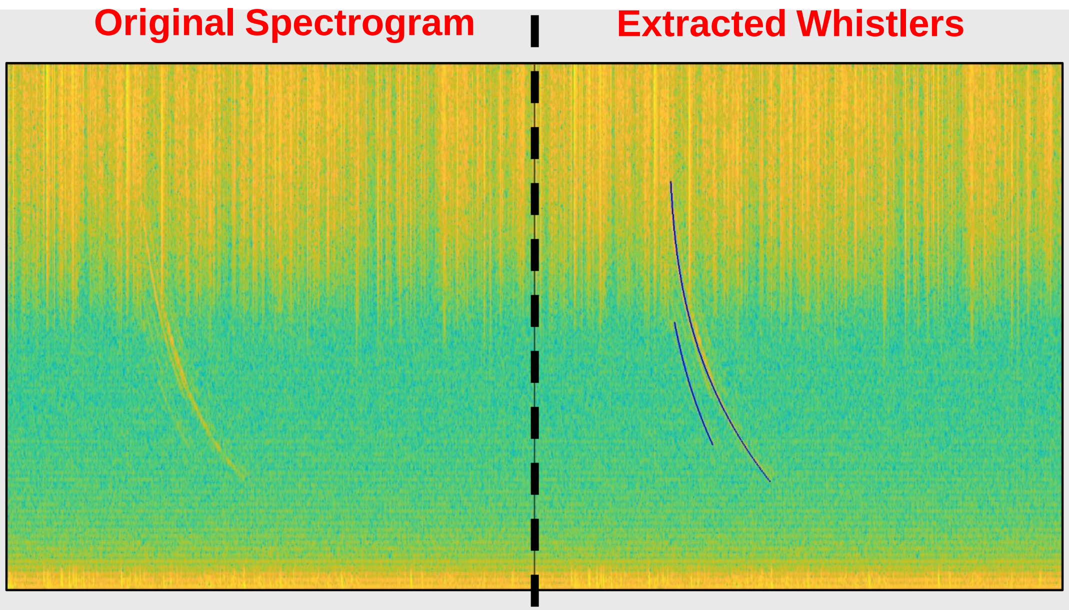

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Supervised Learning

- Supervised Learning describes machine learning models that are trained with labeled “ground truth” data.

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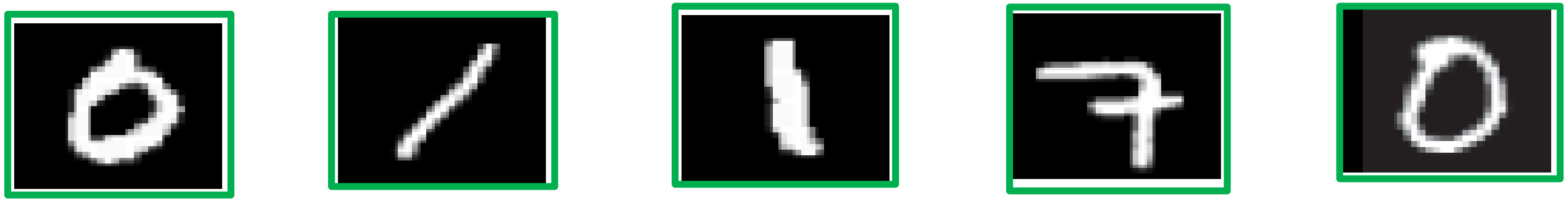
Input Cases



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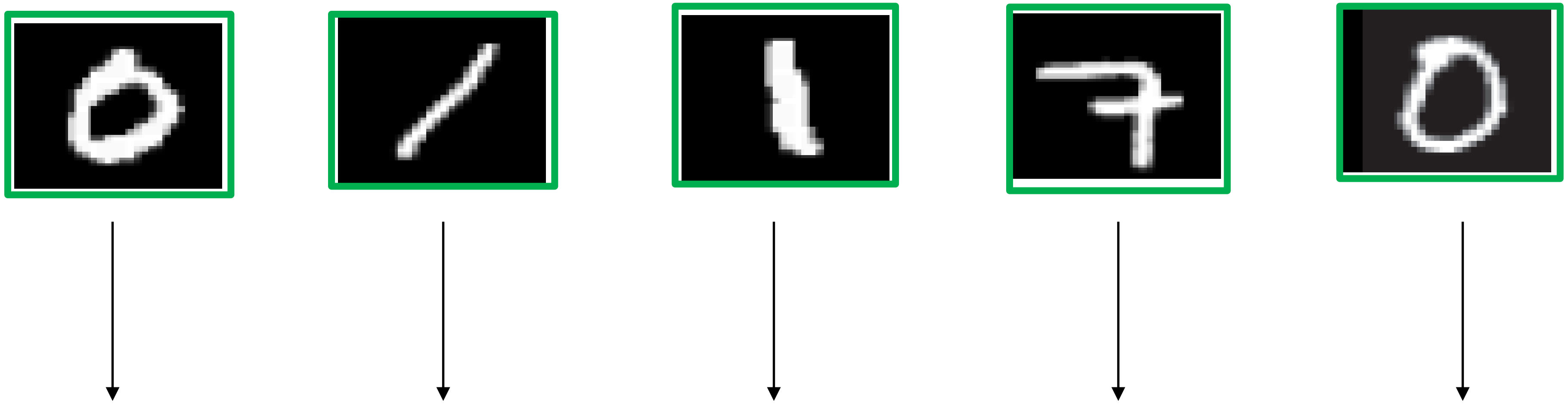
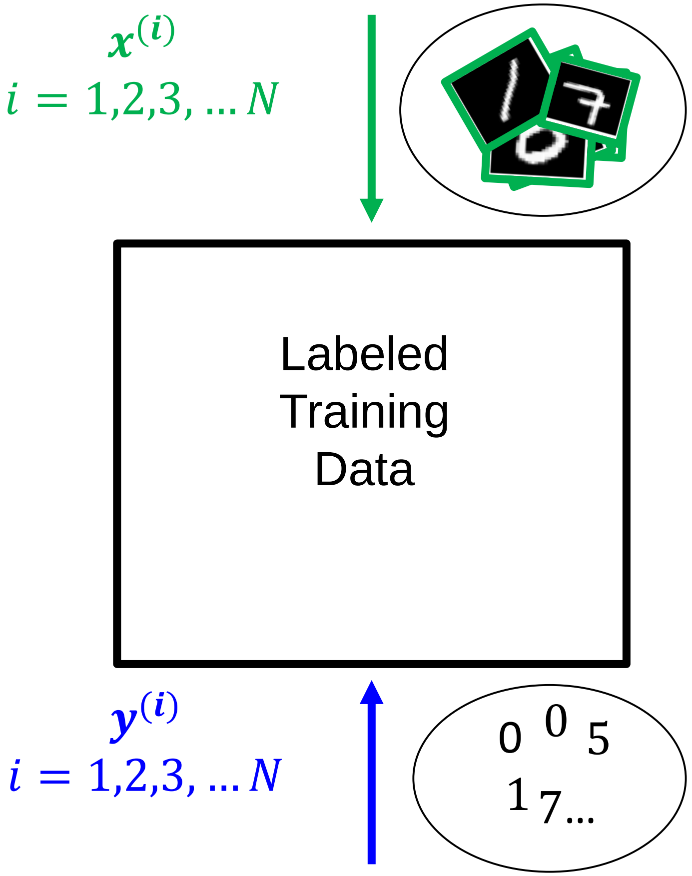


Output Label 0 1 1 7 0

Supervised Learning

The general flow for supervised learning is:



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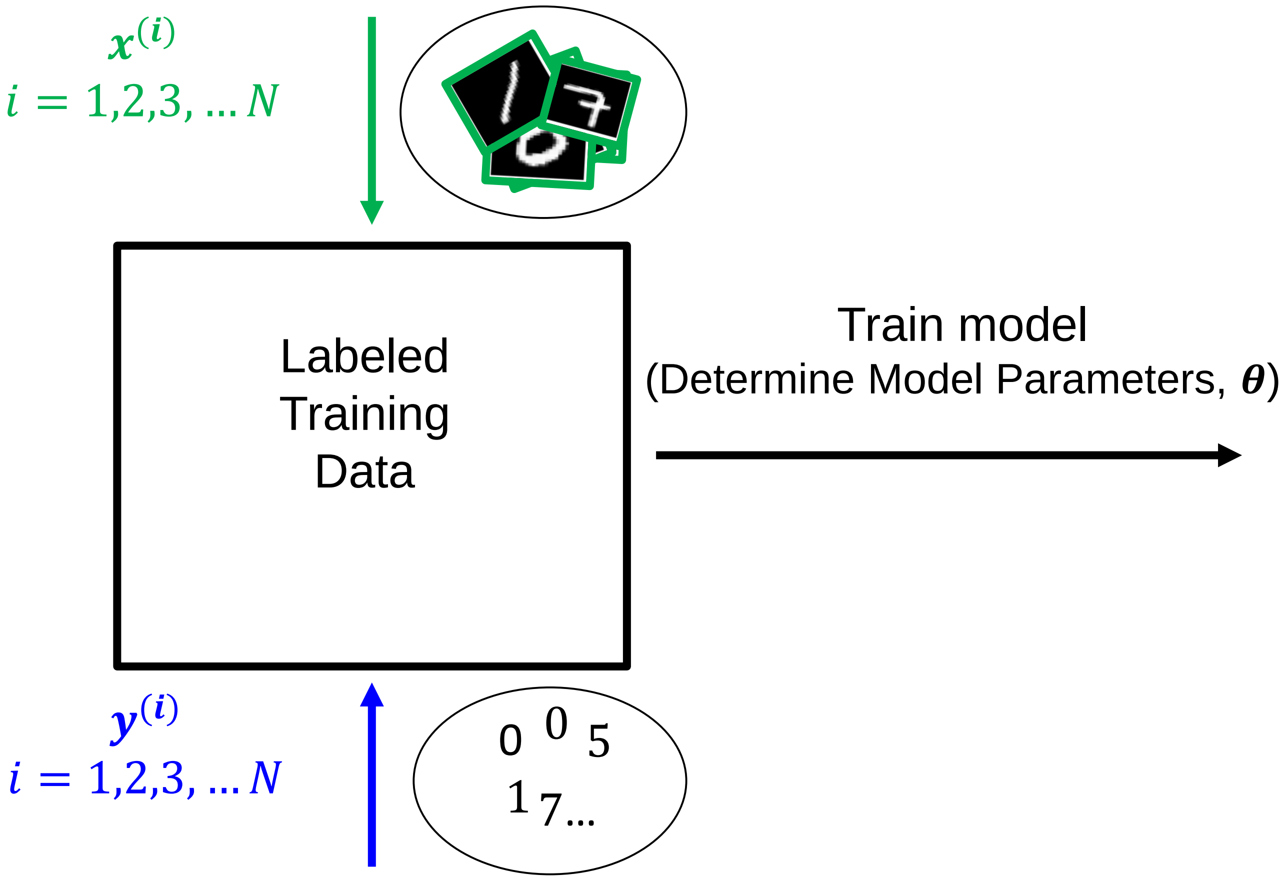

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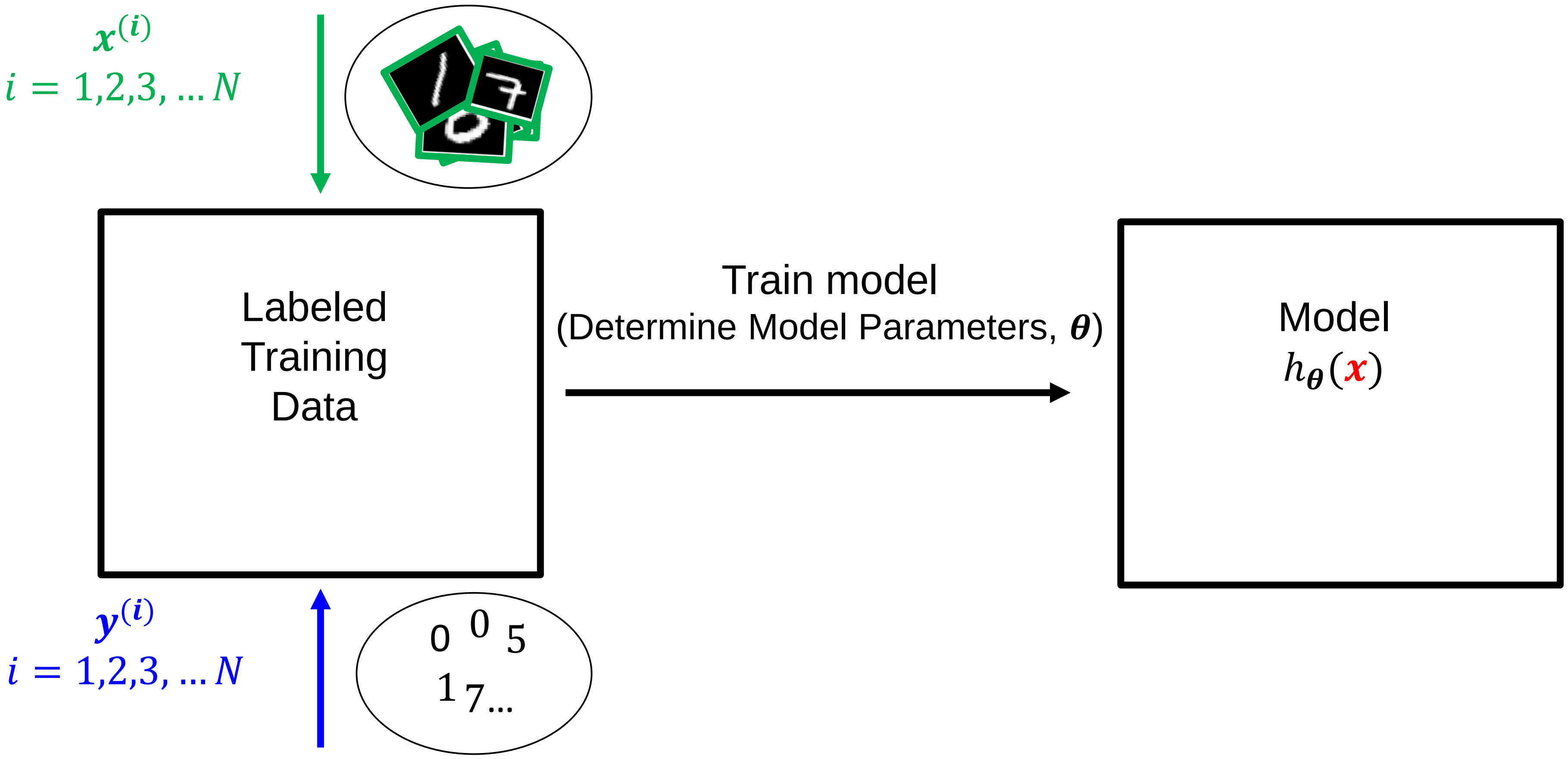

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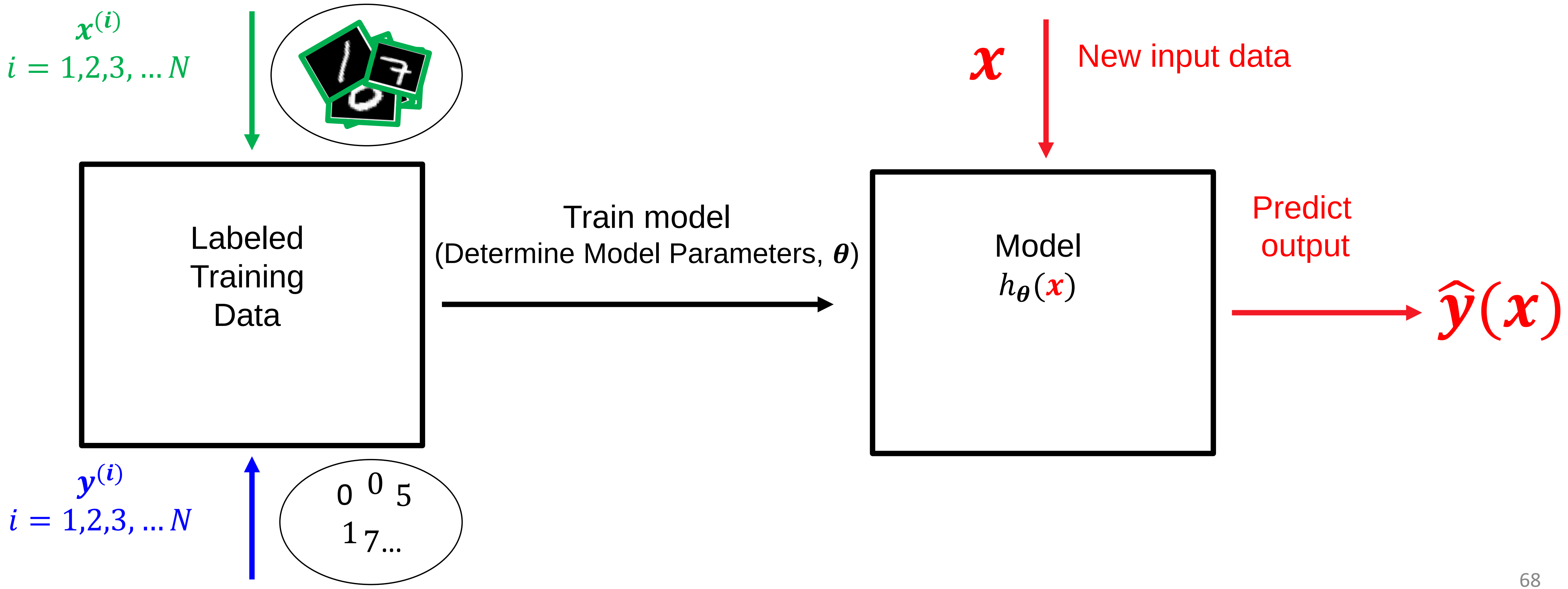
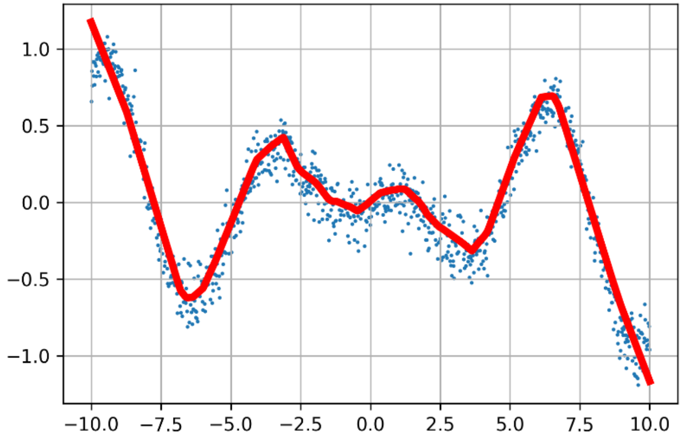


Choice of ML Model

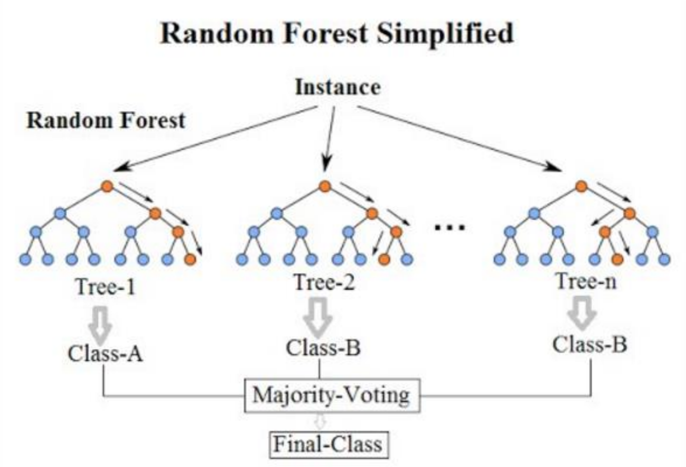
There are several options for models that vary in expressiveness and complexity:

Polynomial Regression



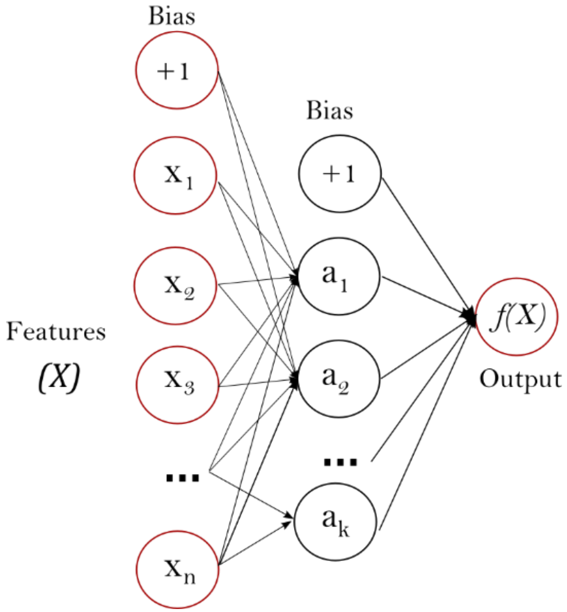
…

Random Forests



…

Neural Networks



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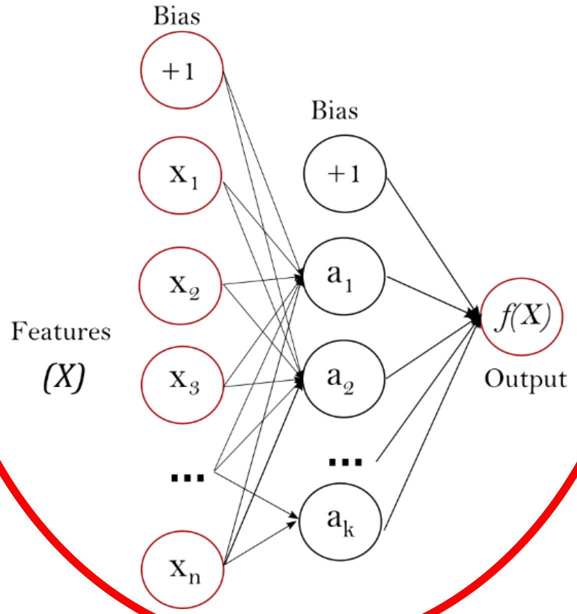
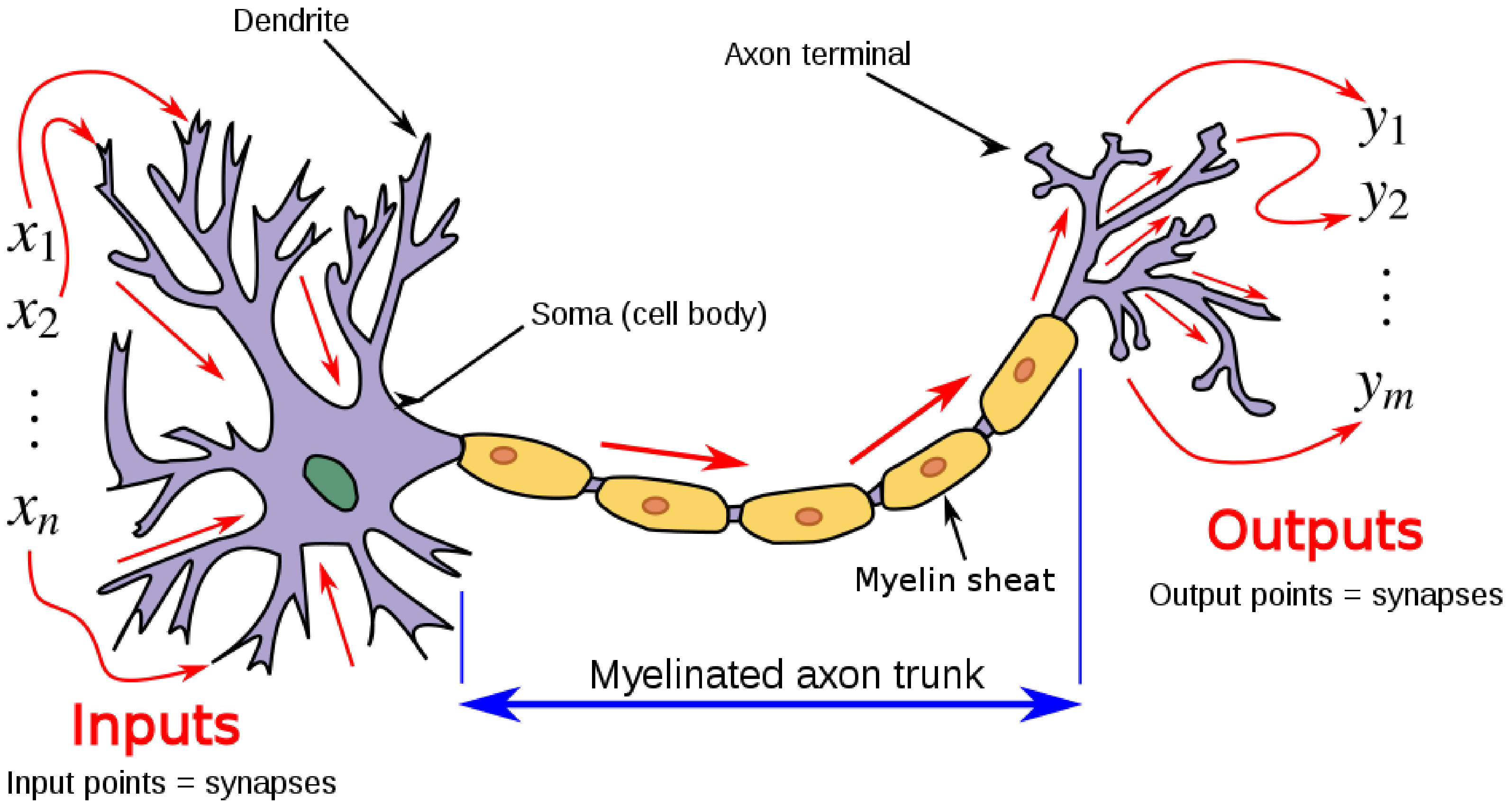
Neural Networks



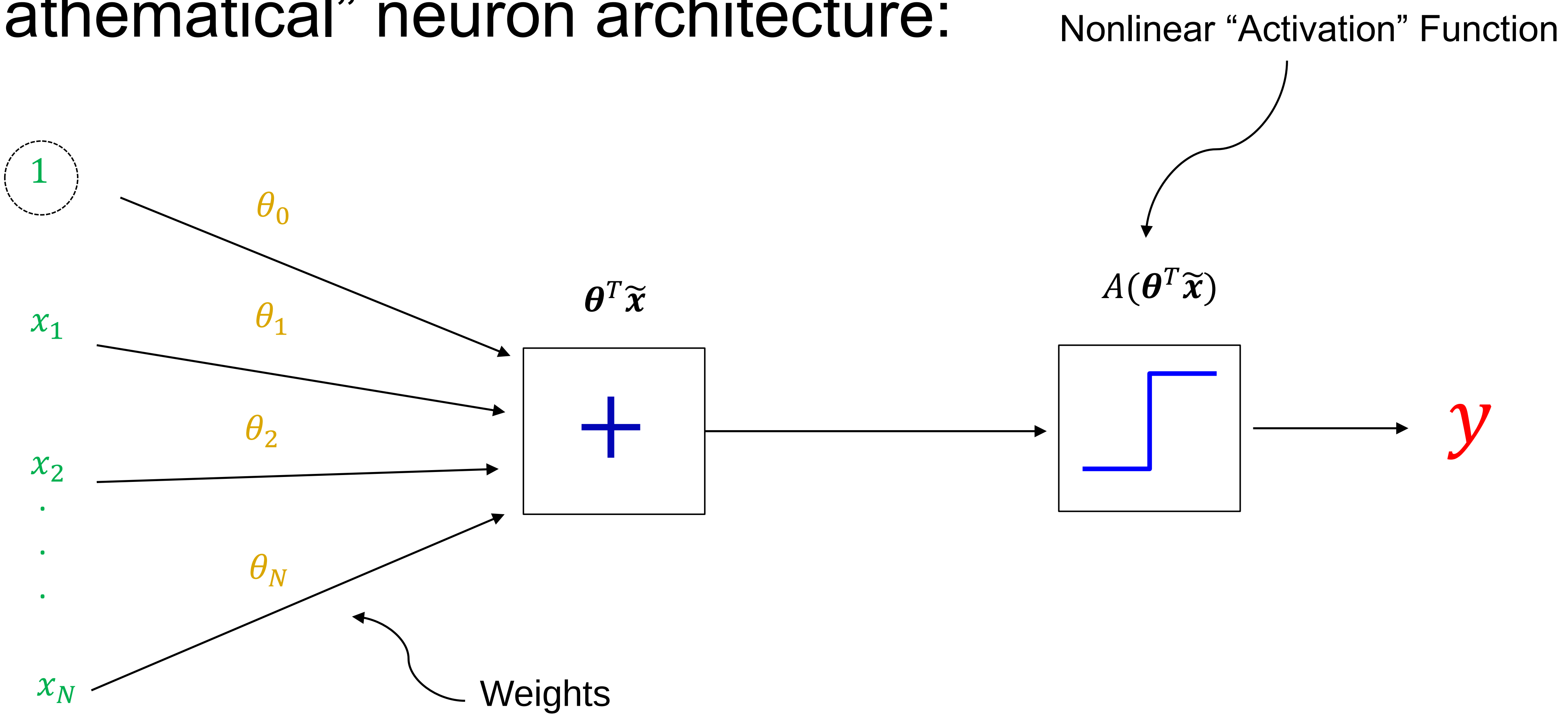
Neural Networks

Neural networks take inspiration from biological neurons:



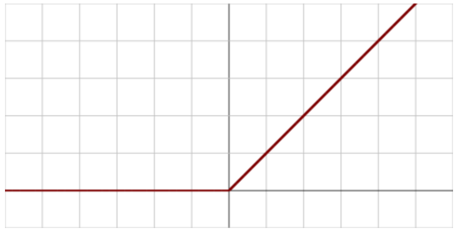
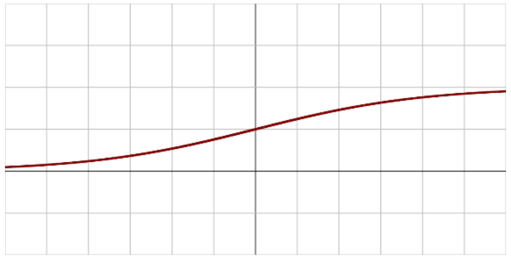
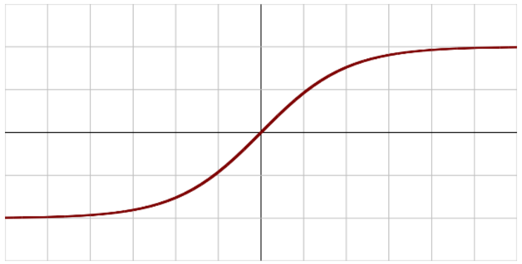
Artificial Neuron

"Mathematical" neuron architecture:



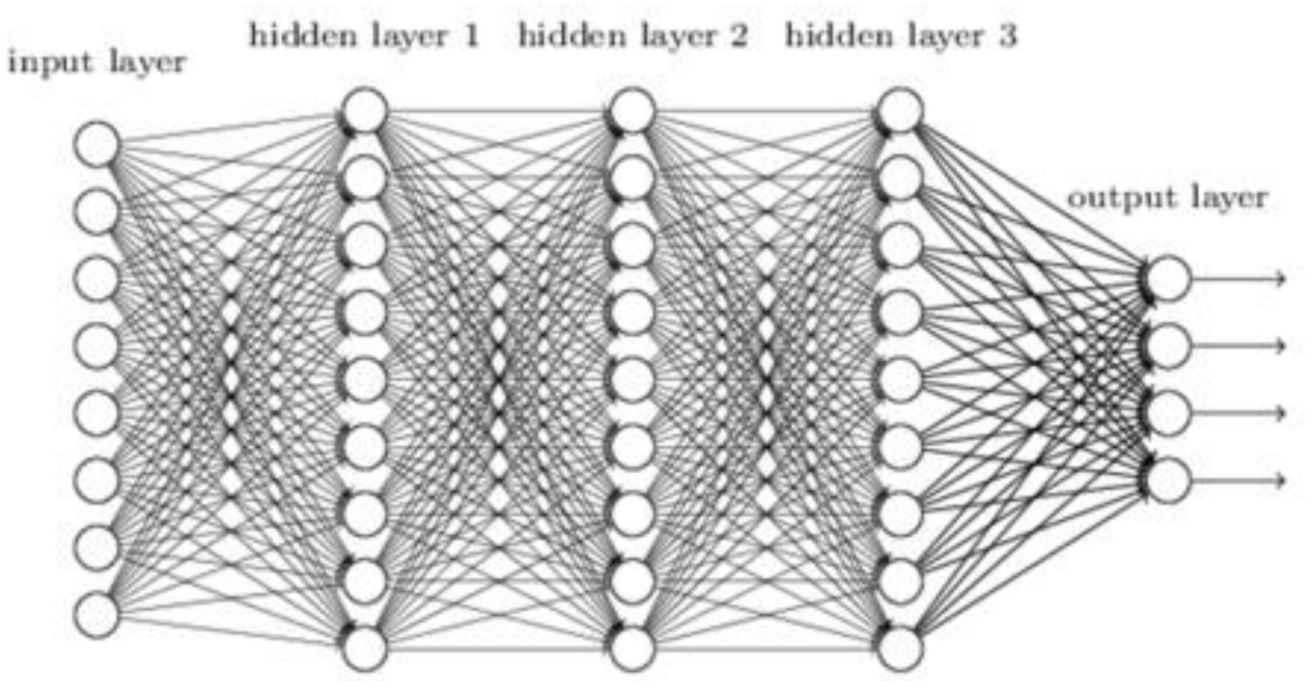
Artificial Neuron

Most common activation functions used in practice:

ReLu	Sigmoid	tanh
$A(x) = \max\{0, x\}$	$A(x) = \frac{1}{1 + e^{-x}}$	$A(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$
		

Neural Networks

- Uses mathematical neurons as building blocks.
- Neural networks can be tuned to map highly nonlinear input-output relationship.
- Sometimes called a Universal Approximator.



Outline

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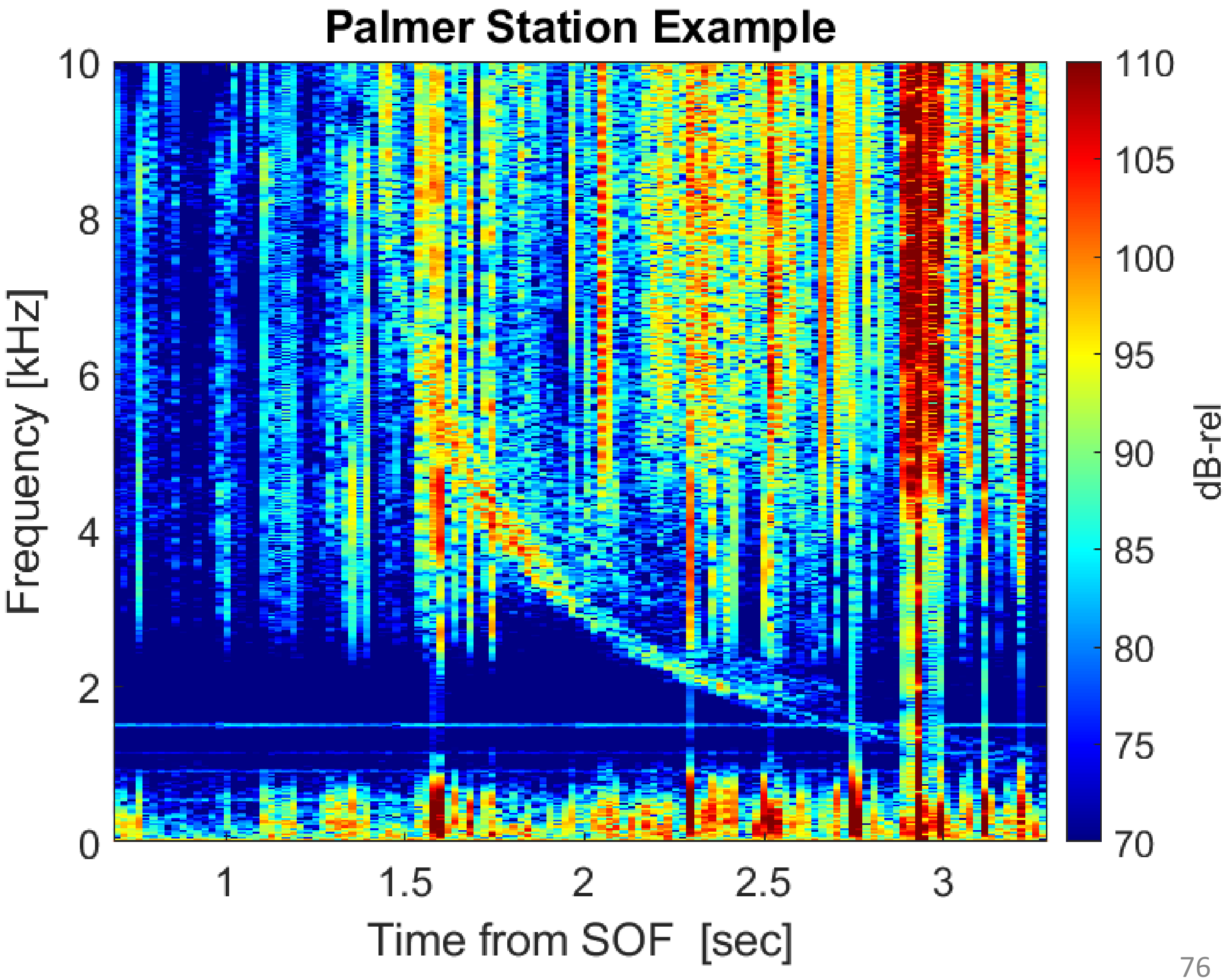
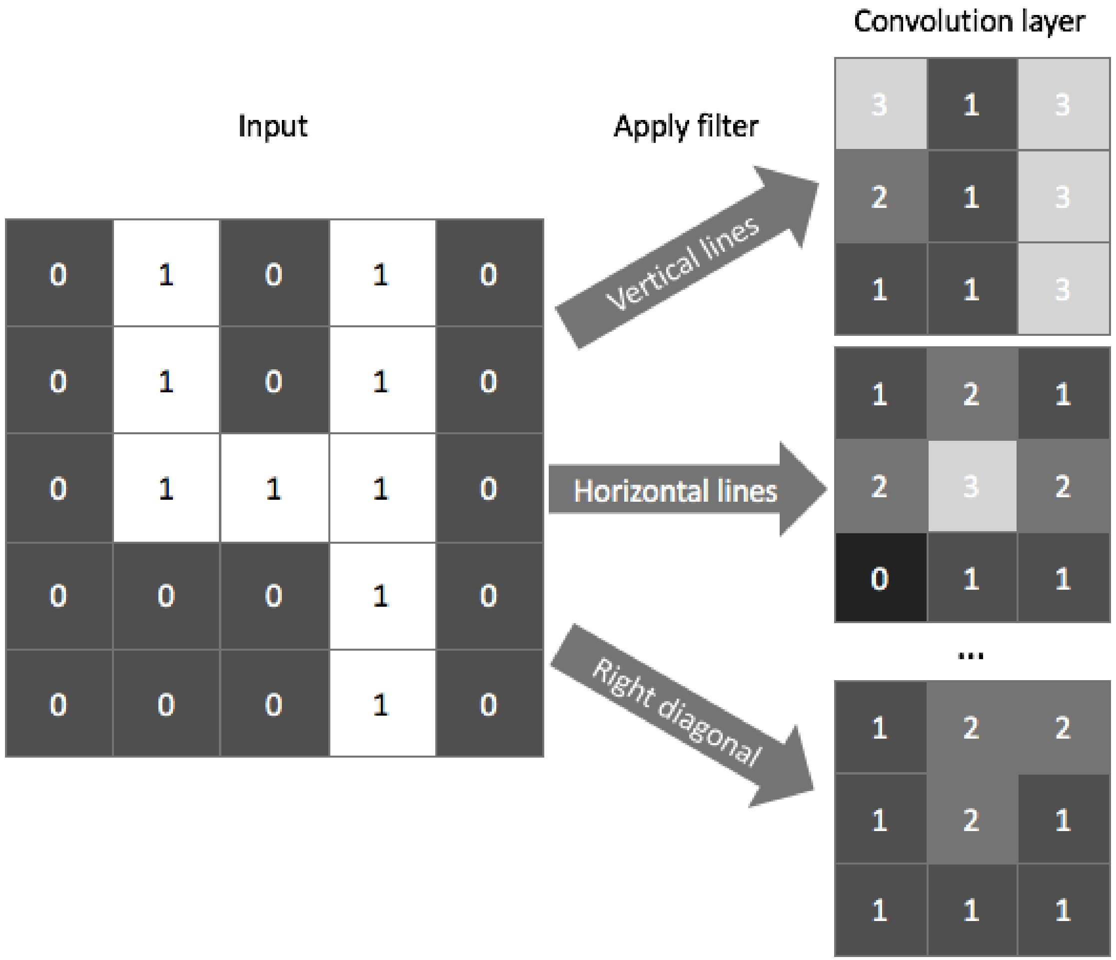
Extraction of Whistlers

- Spectrograms can be treated as "images".
- Whistlers are the "objects" in the images.
- When dealing with images, a Convolutional Neural Network (CNN) is a more efficient starting point.



Convolutional Neural Networks

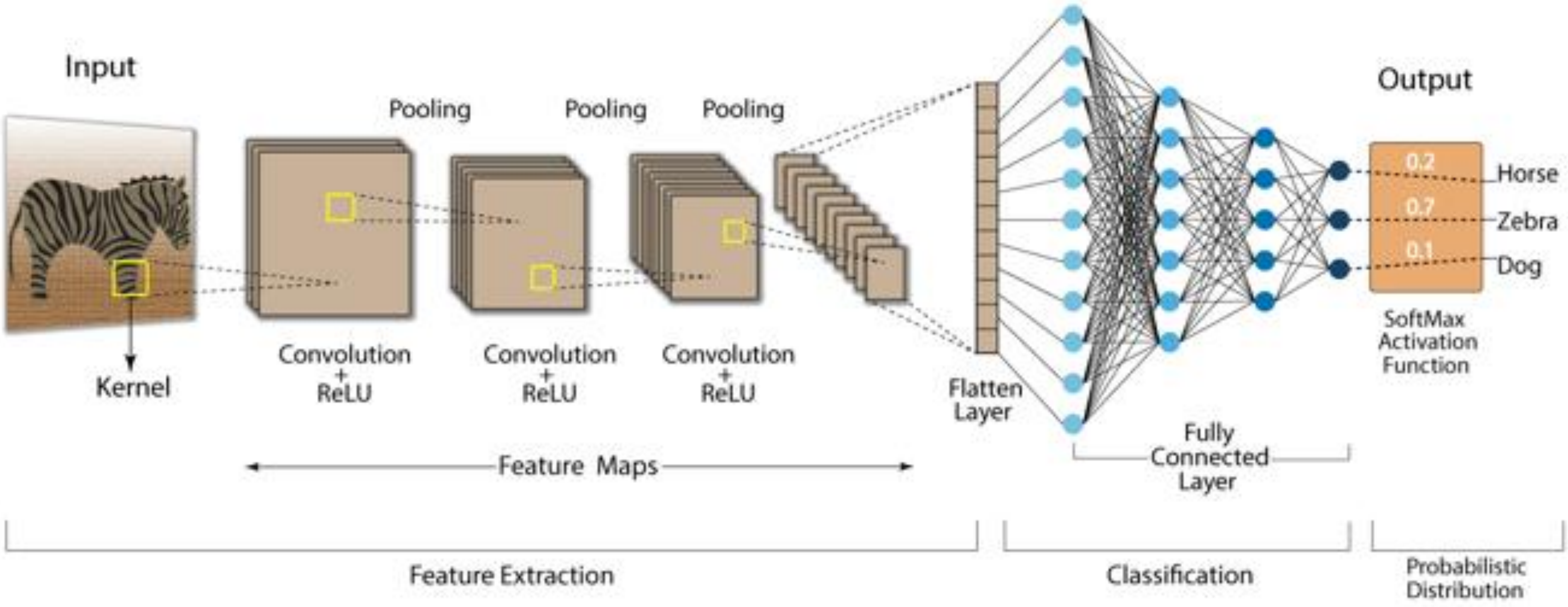
- 1080p images have ~2M pixels…too many features for a standard neural network.
- A better approach is to first extract higher level features (edges, waviness, etc.).
- Convolutional Neural Networks (CNN) learn convolutional filters to reduce dimensionality.



https://www.jeremyjordan.me/convolutional-neural-networks/

Convolutional Neural Networks

End to end architecture of CNN:



https://developersbreach.com/convolution-neural-network-deep-learning/

Mask Regional CNN

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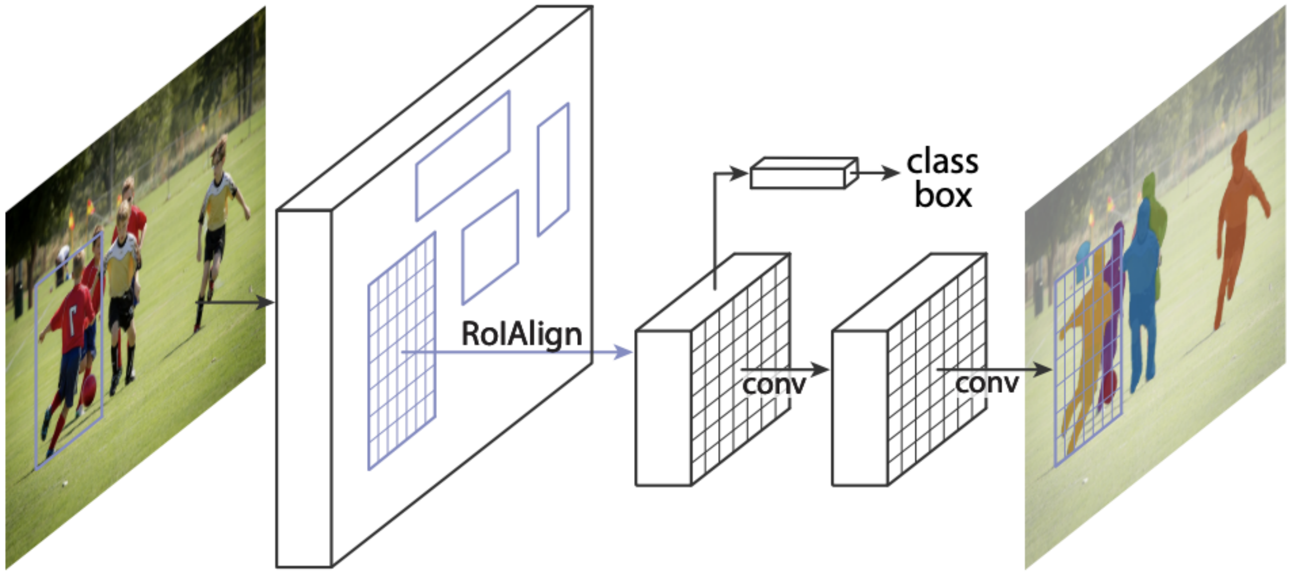
- Mask Regional Convolutional Neural Network (MRCNN) was originally created by Facebook AI Research for object detection/extraction.

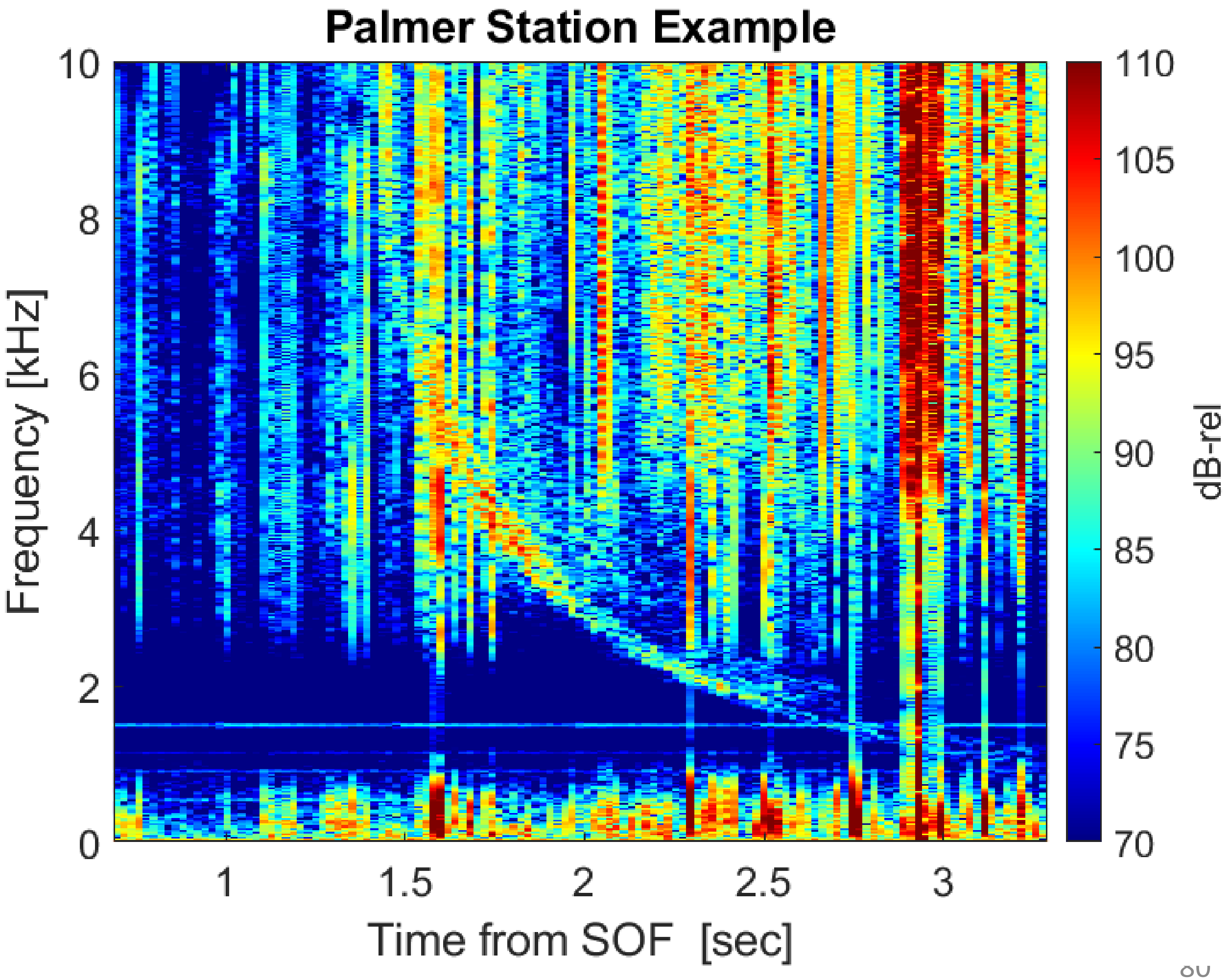
- Has two major features:
  - ➢ Classifies objects.
  - ➢ Determines pixels (mask) corresponding to the object.

"M-RCNN"
[He et al.,2018]



Application to Whistlers

- Spectrograms can be treated as “images”.
- Signals of interest are “objects”.
- The model is being trained on:
    - ➢ Whistlers
    - ➢ Chorus bands
    - ➢ Hiss bands
    - ➢ Triggered emissions
    - ➢ CW/Transmitter signals



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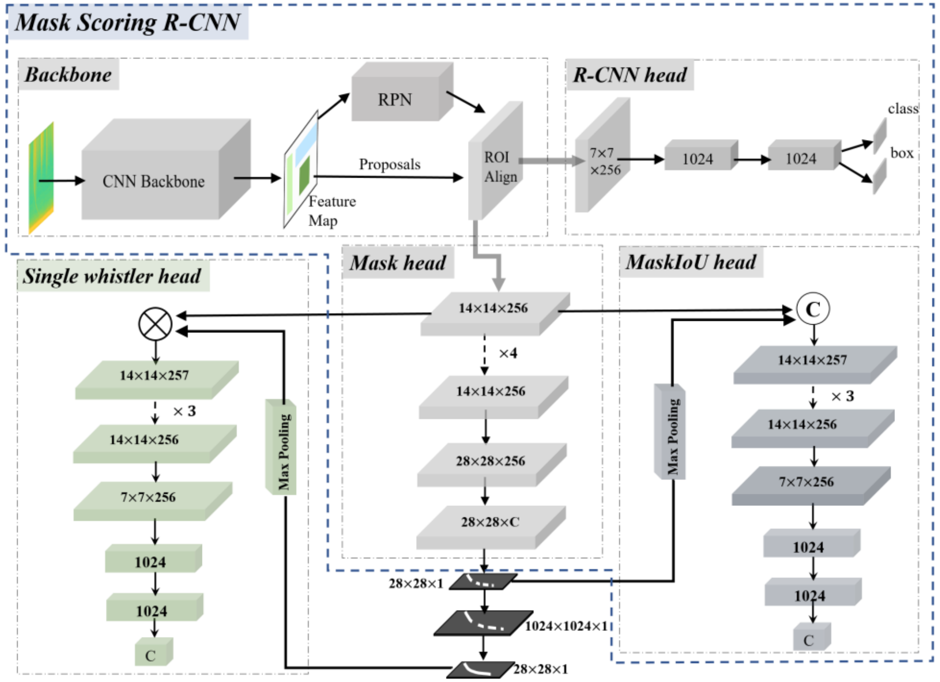
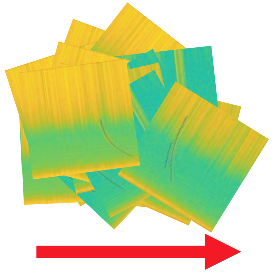
MSRCNN Results

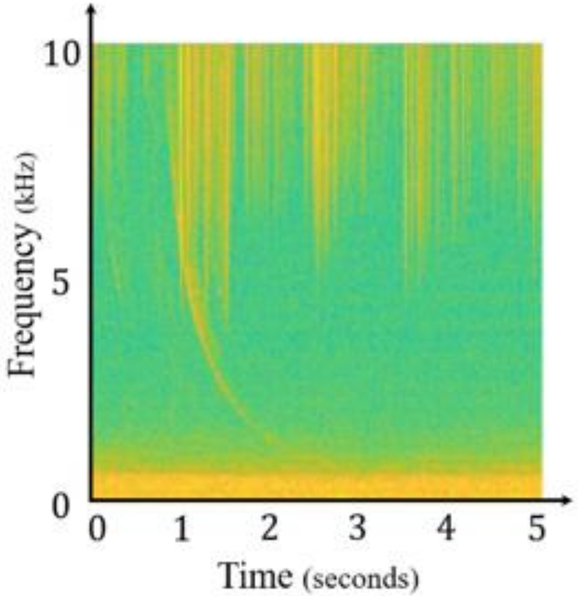
- Mask *Scoring* Regional Convolutional Neural Network (MSRCNN) is typically used for object detection/extraction in images.
- Spectrograms are treated as images, whistlers are the objects.

[Harid et al., 2021]

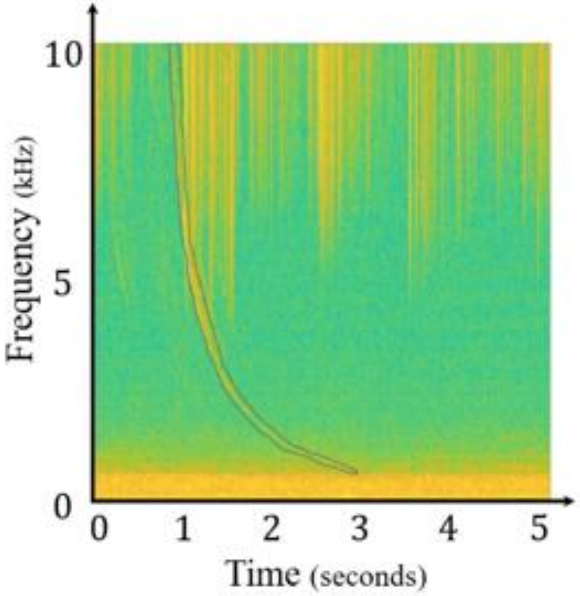




Original Spectrogram



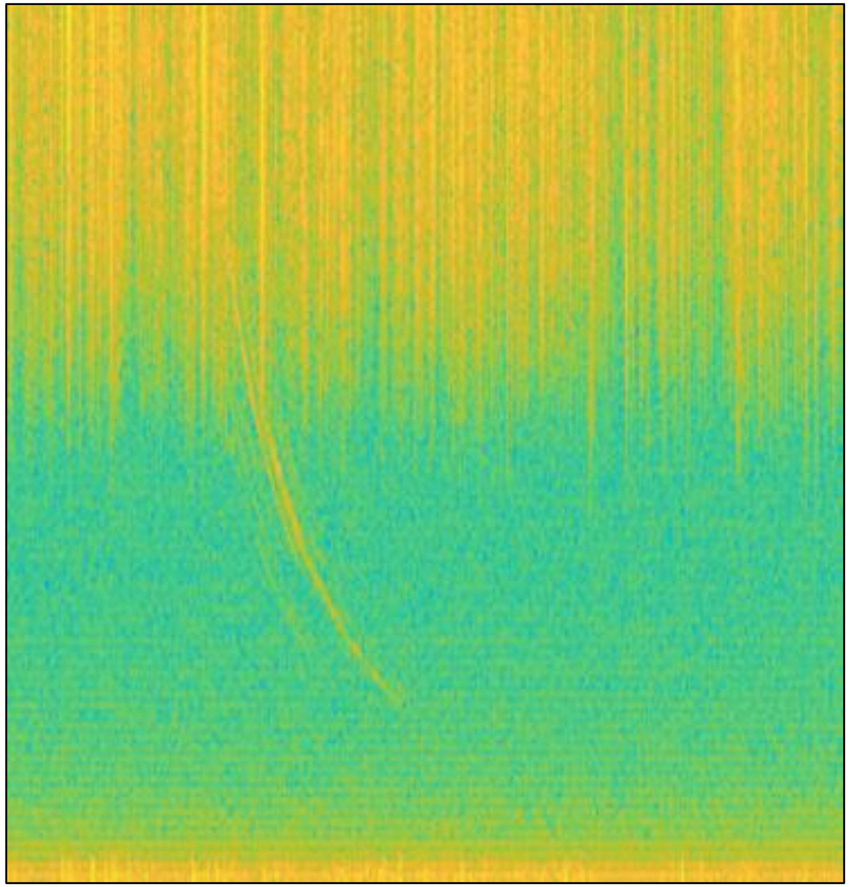
Whistler Track Extraction



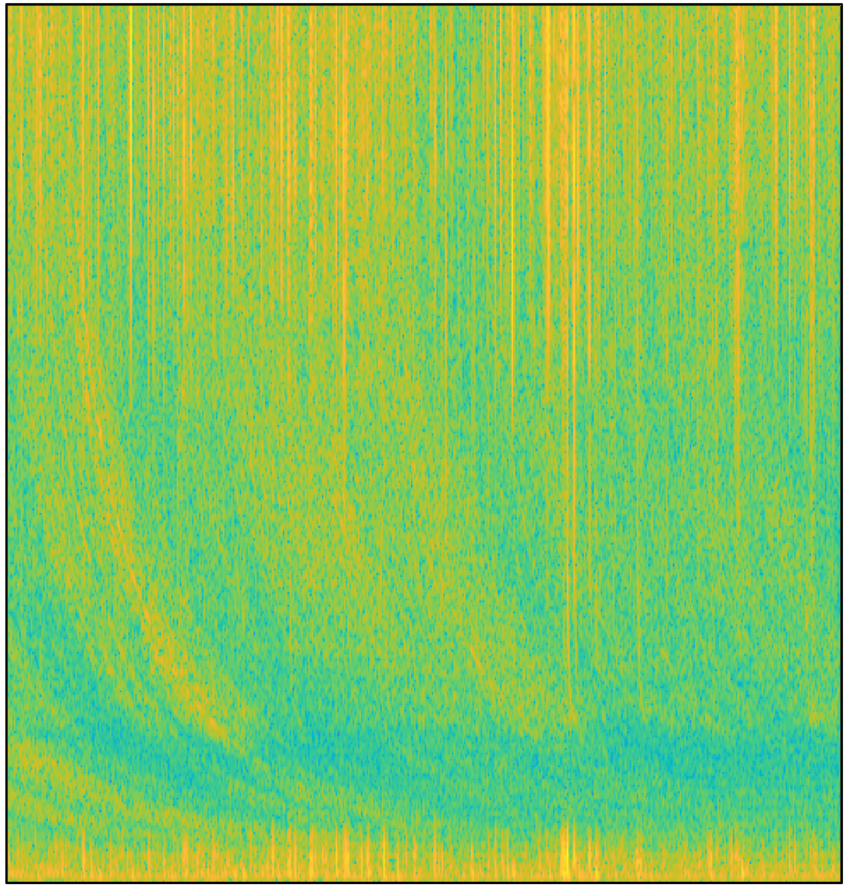
MSRCNN Results

- This ML approach allows for multiple "classes" of whistlers:

Single Whistler



Group Whistlers



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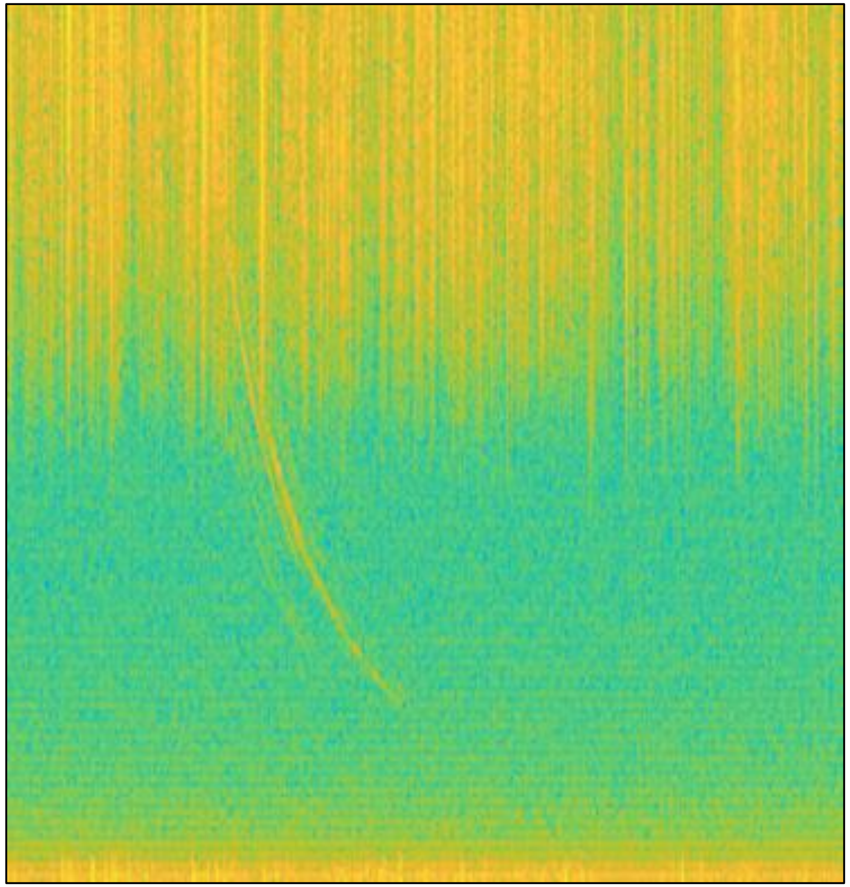
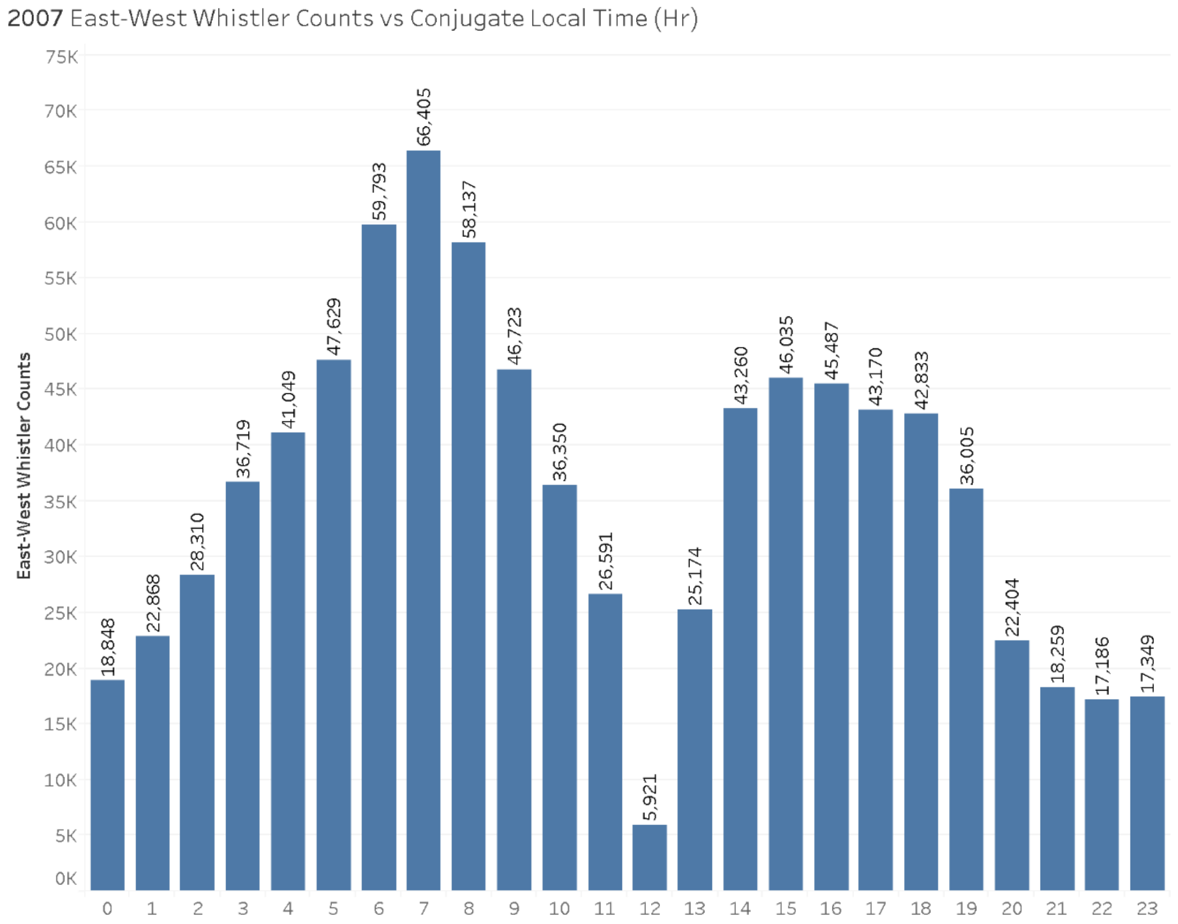


Group Whistlers

Palmer Station: *Diurnal Variation*

- Diurnal variation (relative to conjugate time) is quantified over the entire course of 2007.
- Results show a deep minimum at noon and local maxima at morning/evening (conjugate time).
- Higher whistler counts are observed during daytime compared to nighttime.
- This strong diurnal dependence can provide insight on the geophysical environment (future work).

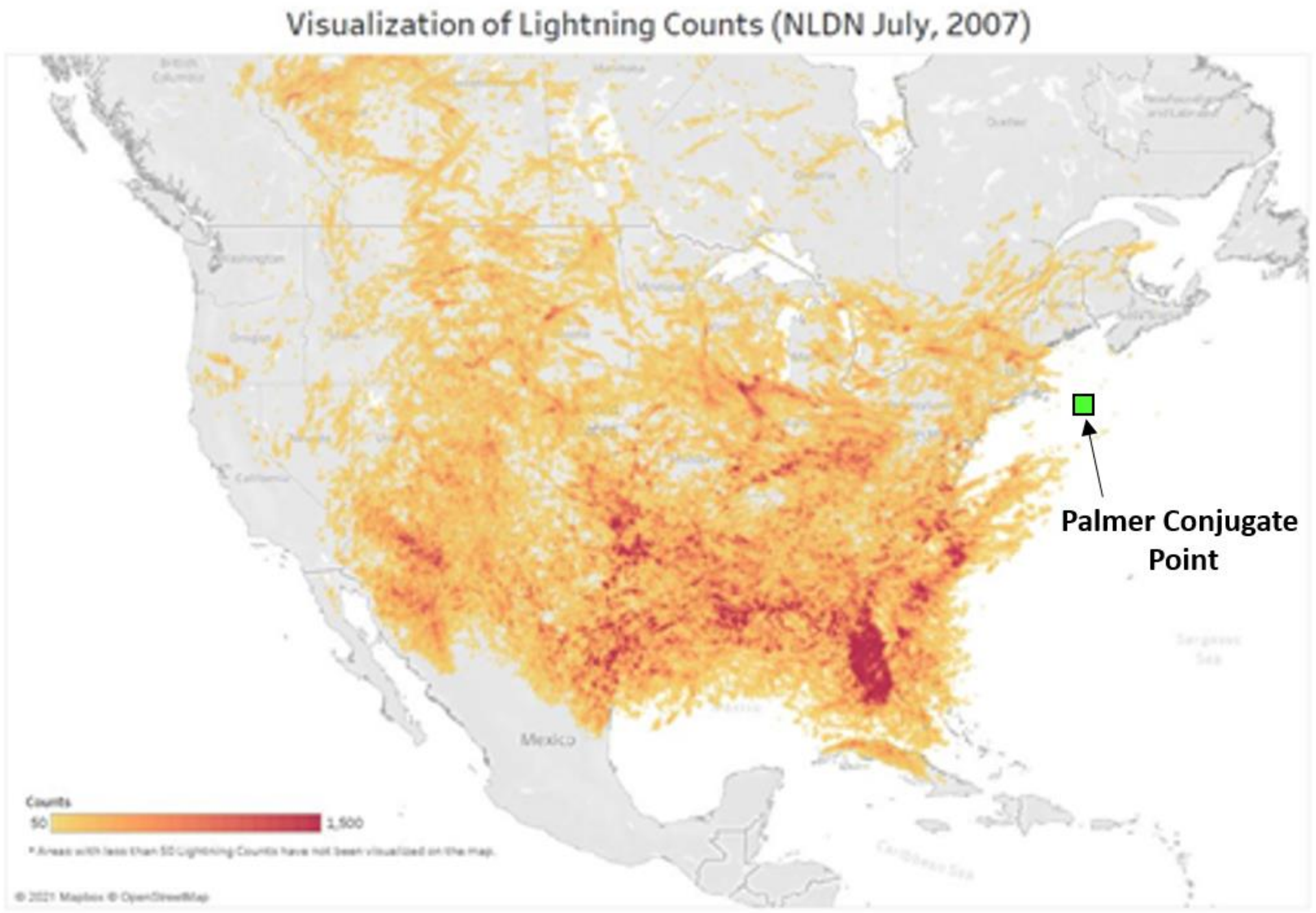


Palmer Station: *Comparison to Lightning*

- Palmer conjugate point is located on the east coast of North America.

- Source of whistlers are from lightning across North America.

- Palmer whistlers can be compared to lightning data in North America.



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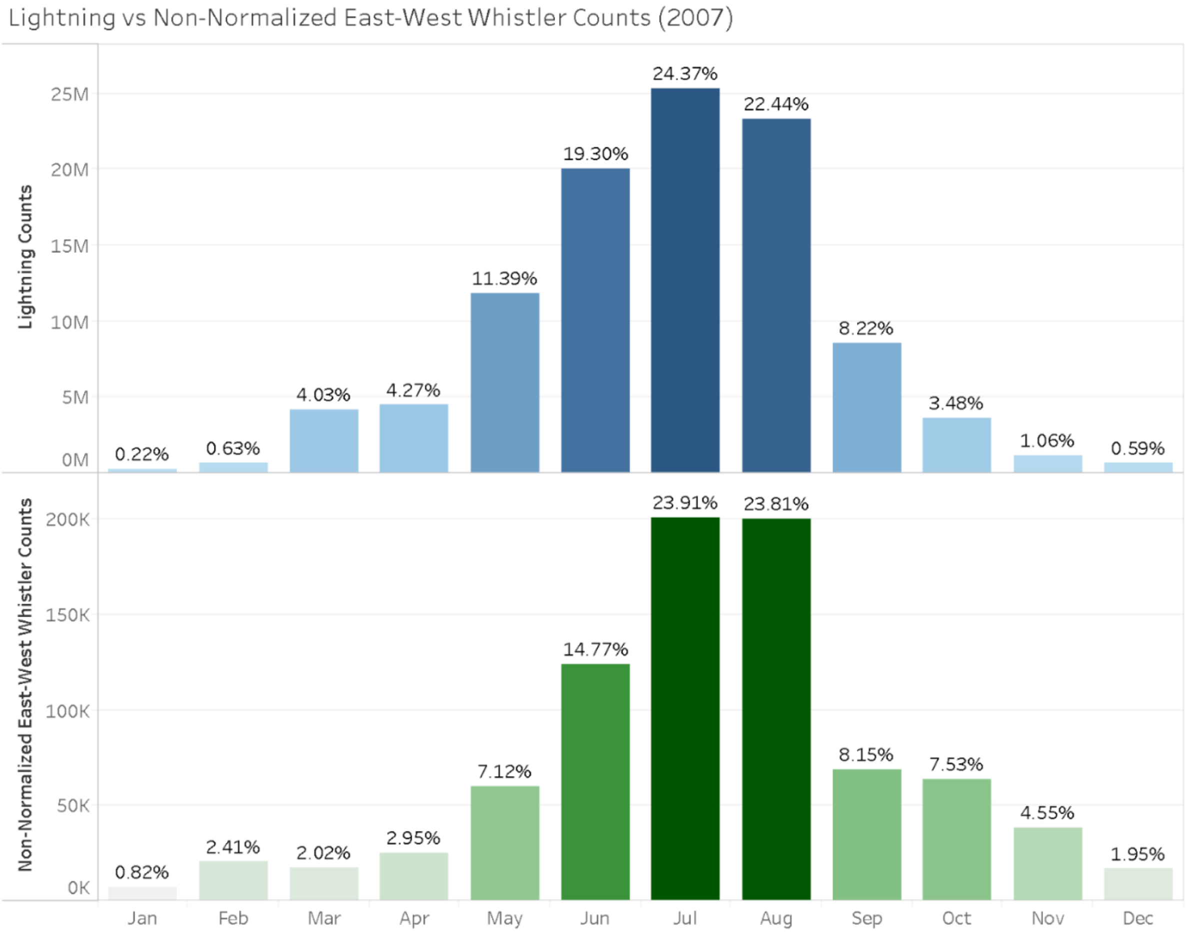
Palmer Station: *Comparison to Lightning*

- Results are compared to lightning data in North America using NLDN (National Lightning Detection Network).
- Results shows excellent correlation on monthly timescales for ***entirety*** of North American lightning.
- Other geophysical parameters are also likely important and impacting correlation (future work).



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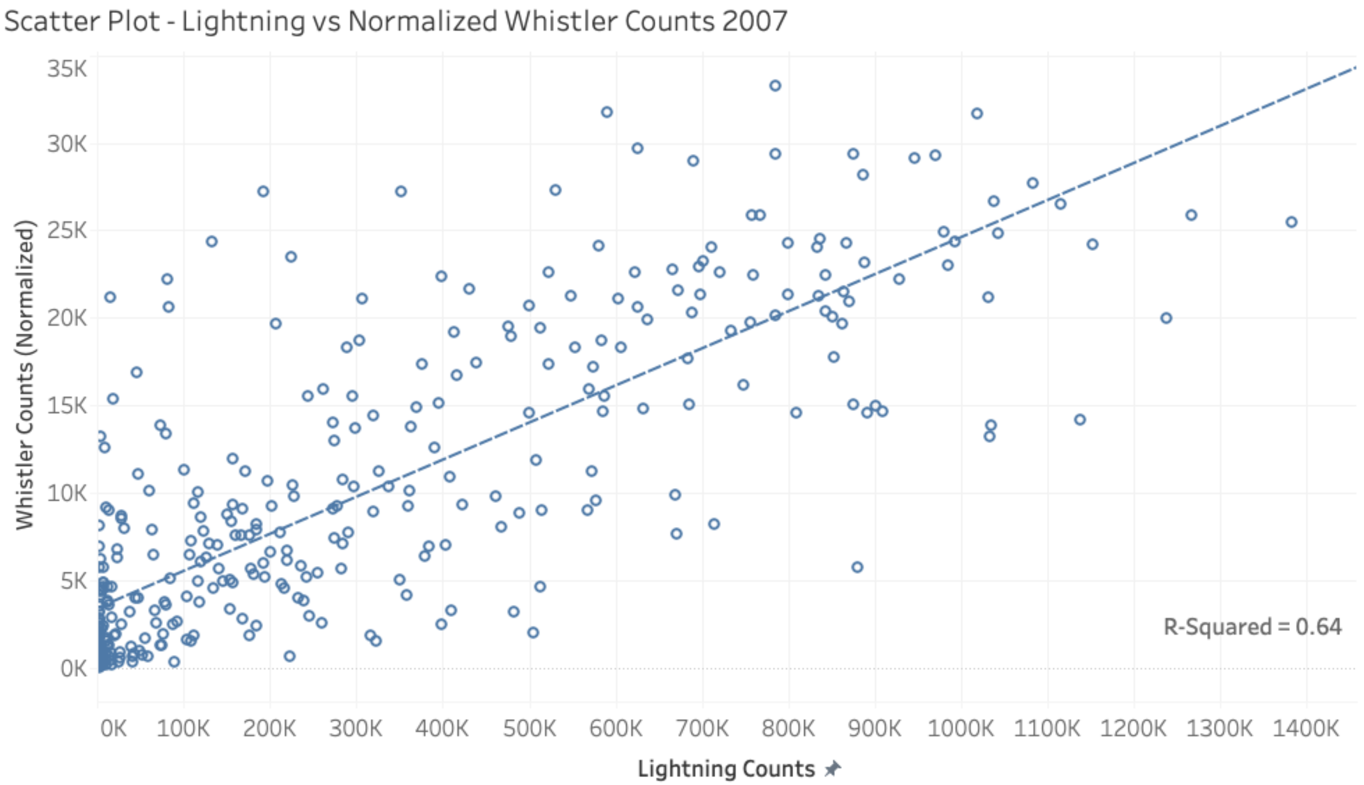
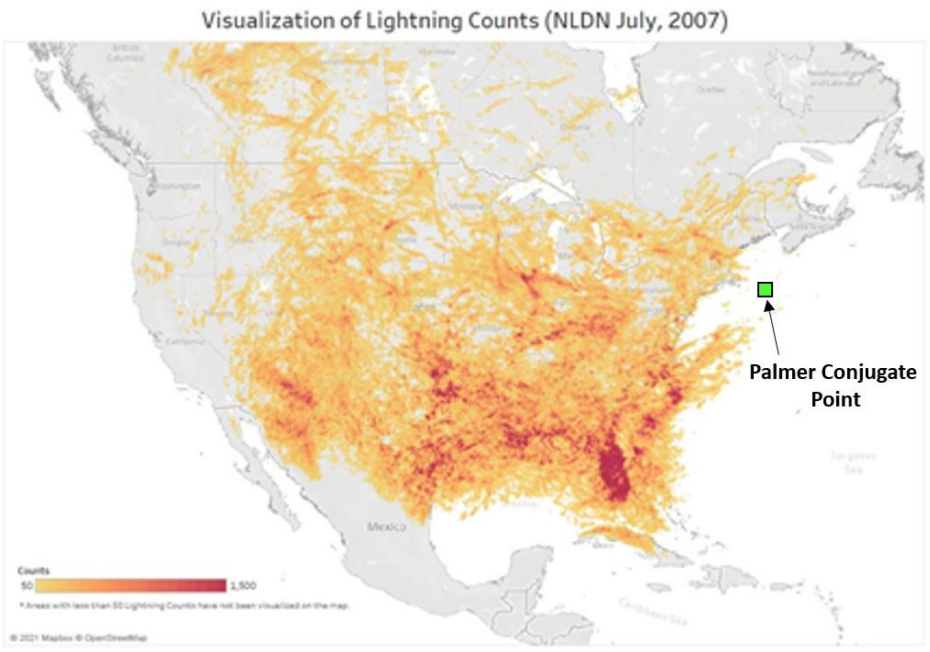


Non-Localization of Whistlers?

- Correlation can be computed as a function of distance from the conjugate point.



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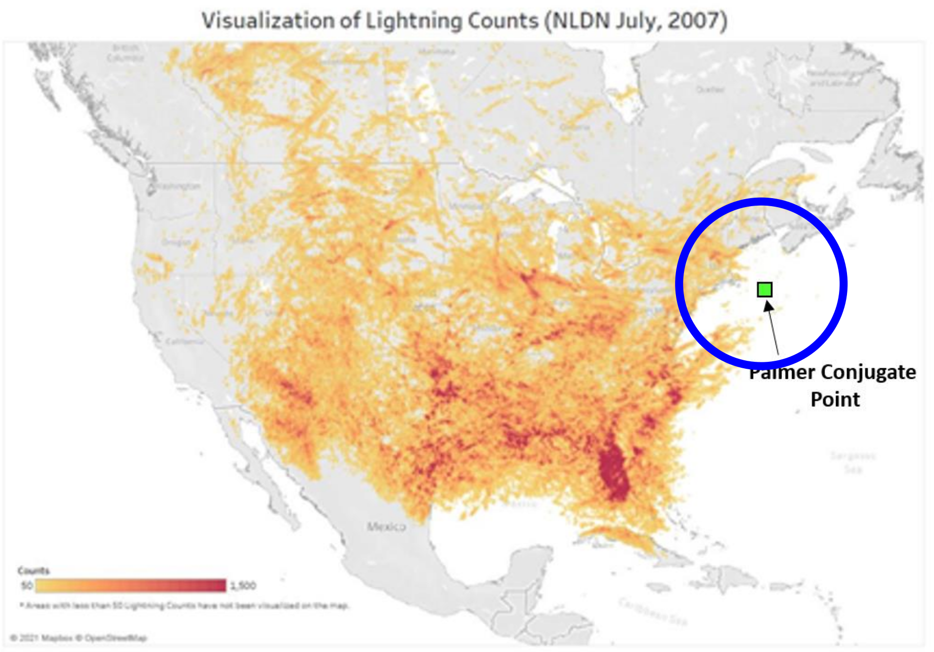

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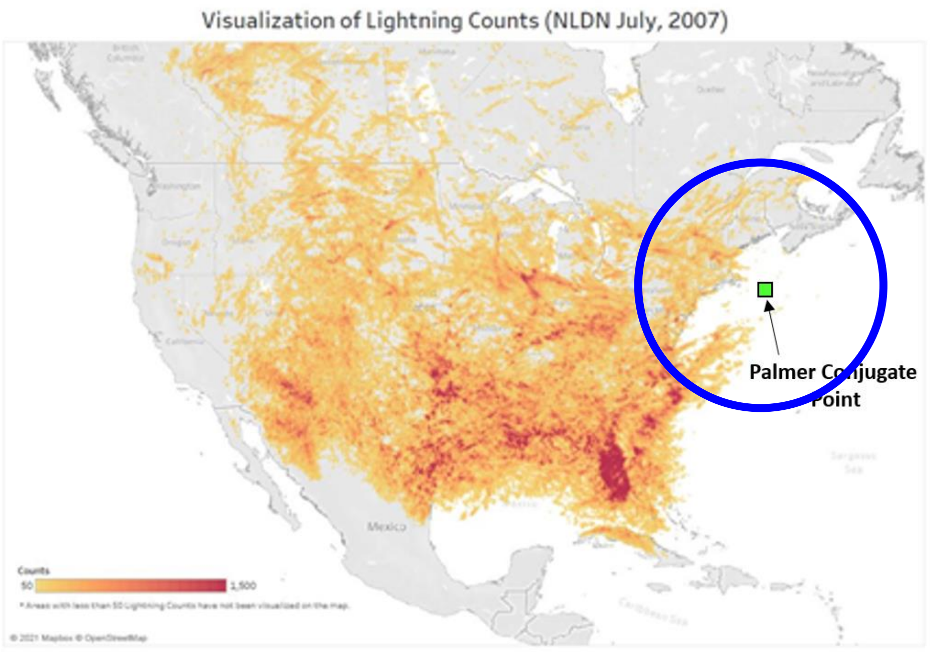

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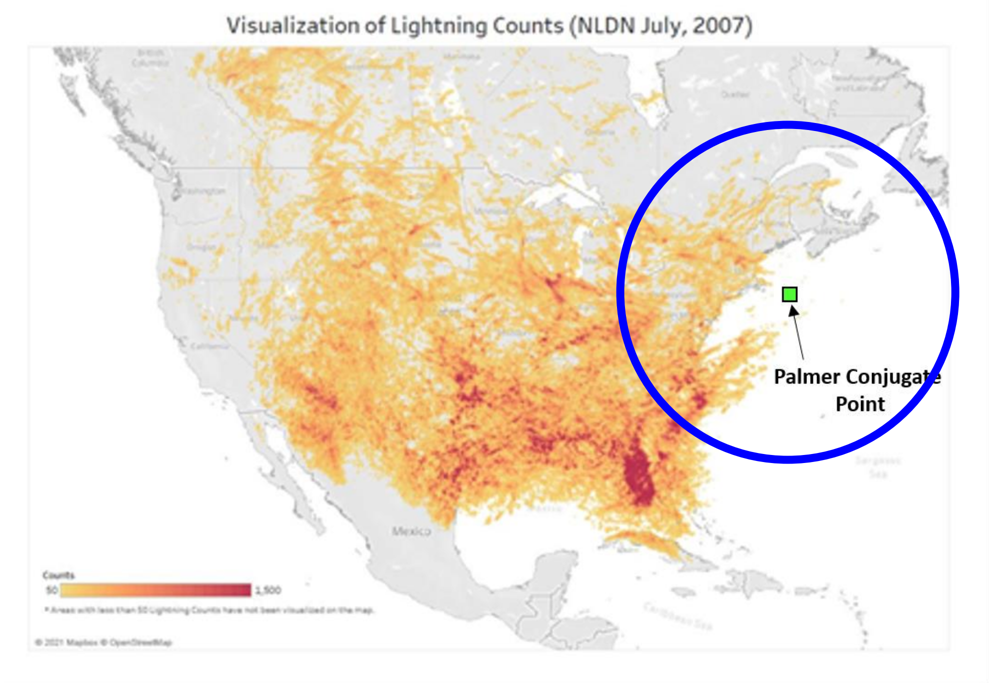

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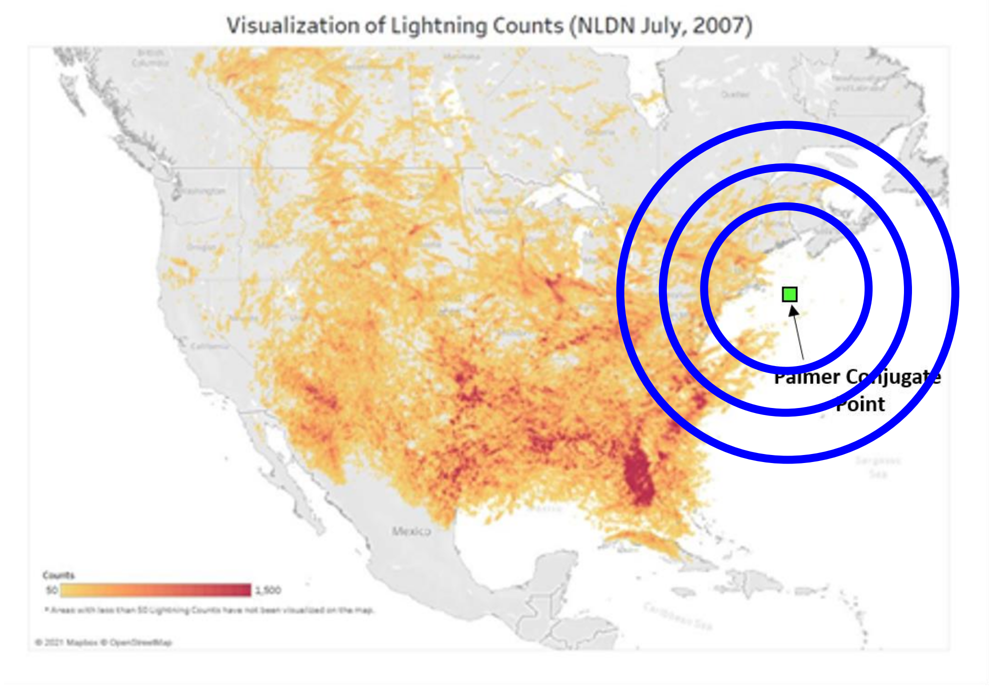
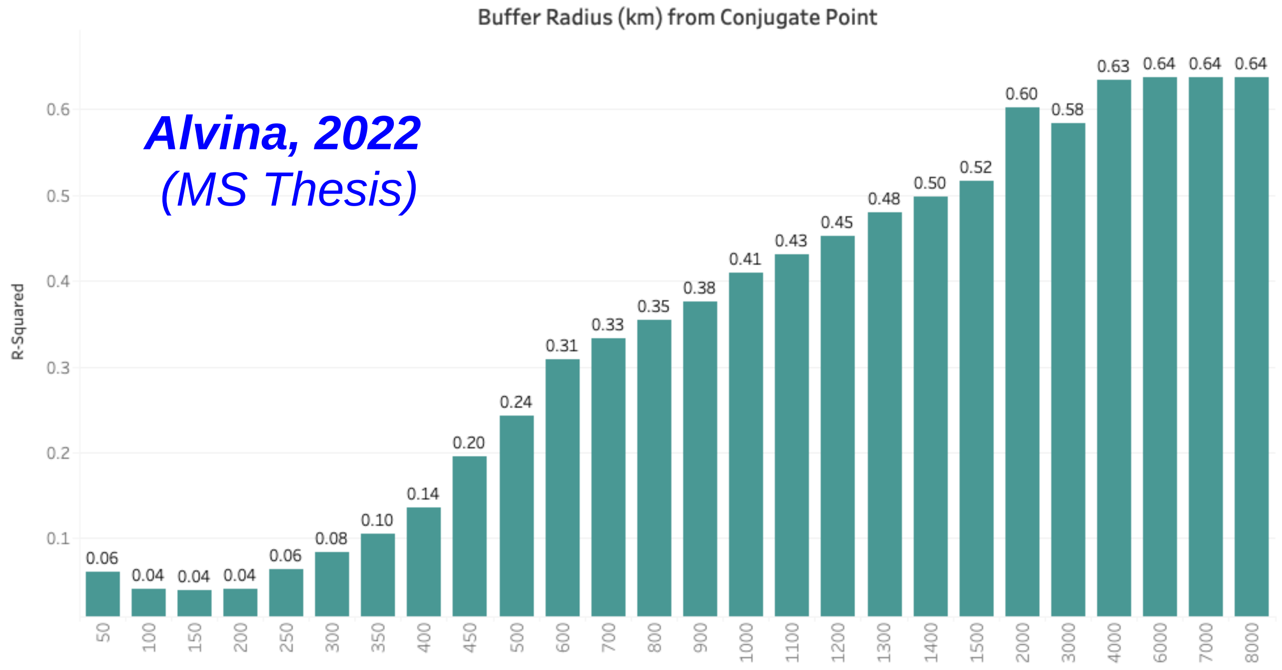
Non-Localization of Whistlers?

- Correlation can be computed as a function of distance from the conjugate point.
- The causative lightning sources might be more spread out than previously thought.



R-Squared values for Buffer Distances (km) from Conjugate Point for Scatter Plots between NLDN and Normalized Whistler Counts (2007)



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Other Recent Works

Several research groups are now using machine learning methods for automated VLF signal detection:

- ***Pataki et al., 2022*** - Monitoring Space Weather: Using Automated, Accurate Neural Network Based Whistler Segmentation for Whistler Inversion
- ***Maslej-Krešňáková et al., 2021*** - Automatic Detection of Atmospherics and Tweek Atmospherics in Radio Spectrograms Based on a Deep Learning Approach
- ***Jin et al., 2021*** - Advances in the automatic detection algorithms for lightning whistlers recorded by electromagnetic satellite data
- ***Wang et al., 2020*** - Classification of VLF/LF Lightning Signals Using Sensors and Deep Learning Methods
- ***Konan et al., 2020*** - Machine Learning Techniques to Detect and Characterise Whistler Radio Waves
- ***Ahmad et al., 2019*** - Automatic Detection of Lightning Whistlers Observed by the Plasma Wave Experiment Onboard the Arase Satellite Using the OpenCV Library

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Summary

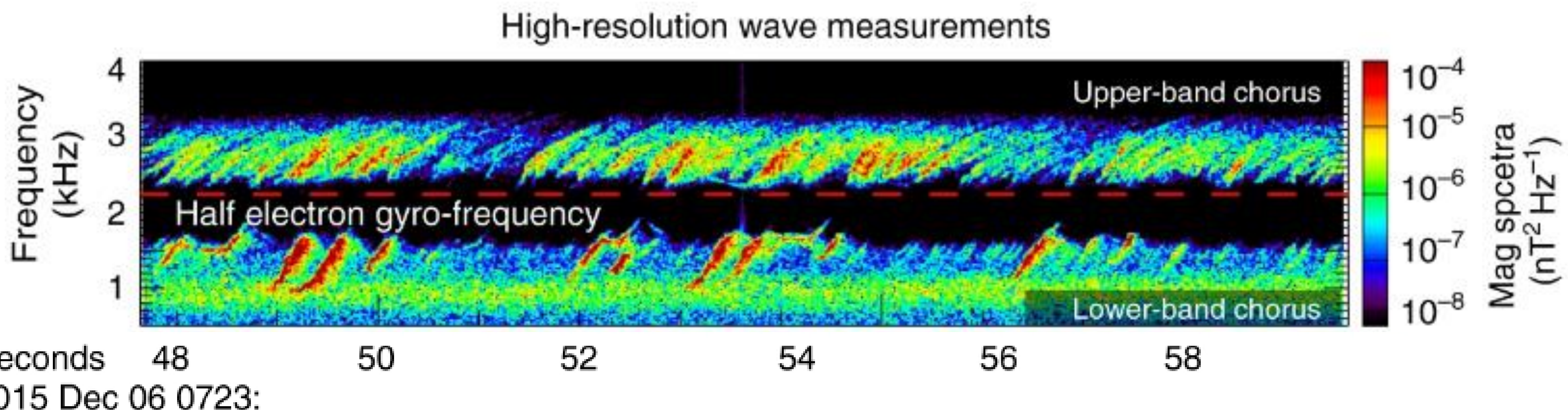
- ELF/VLF waves are ubiquitous in near-Earth space.
- Waves have frequency-time signatures on spectrograms.
- Large datasets are now available from ground-based and spacecraft measurements.
- We utilized the MSRCNN method for large scale extraction for whistlers from ground-based data.
- Machine learning methods are powerful tools for automatically extracting ELF/VLF signals from spectrogram data.

Future Work

- Other classes of whistler-mode waves also have a characteristic ***frequency-time signature*** on spectrograms.

- The machine learning formalism is general enough that it can be easily extended to other signals

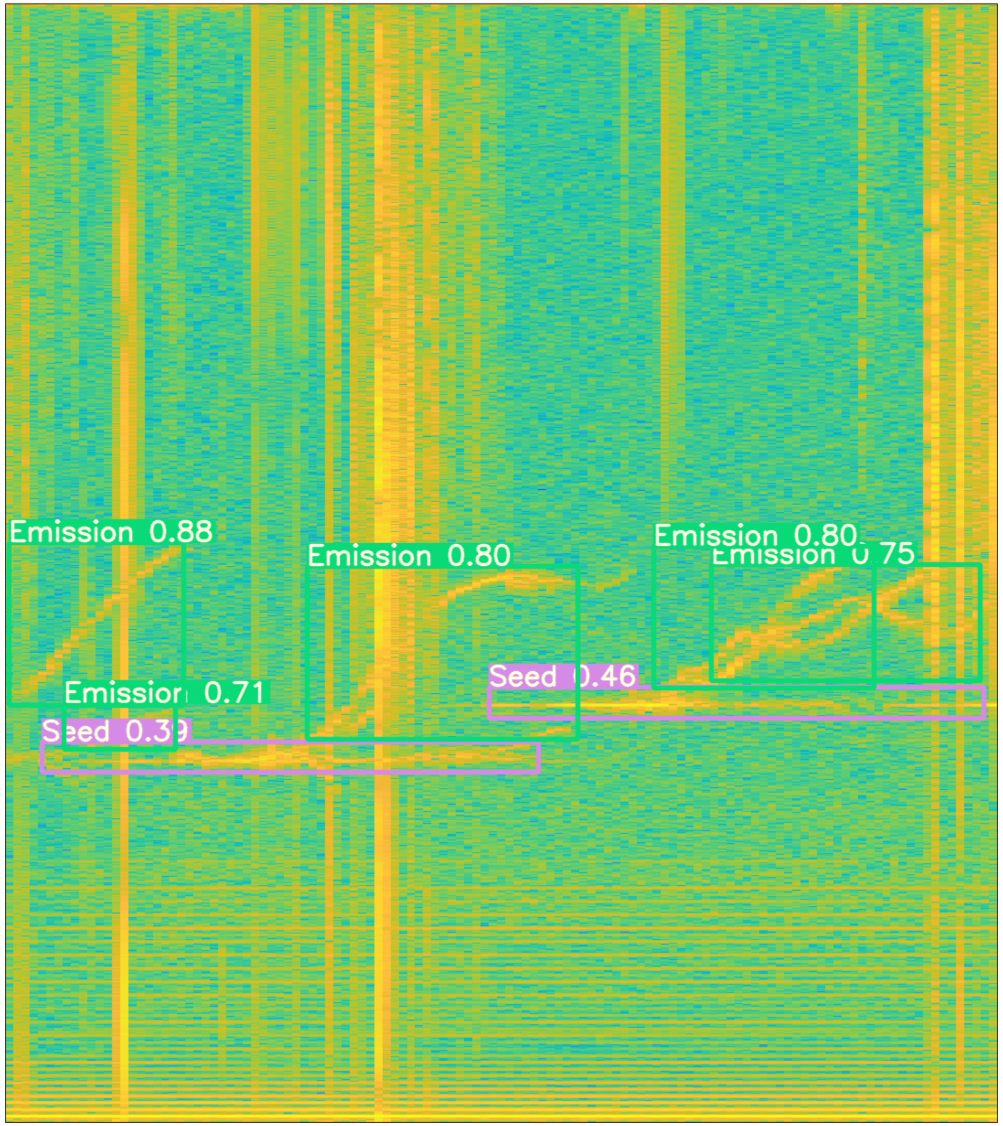
Li et al., 2019



University of Colorado Denver

Future Work

- The model is currently being extended to other signal classes including:
  - Chorus bands
  - Hiss bands
  - Triggered emissions
  - CW/Transmitter signals
- Still very much part of active research…more to come!



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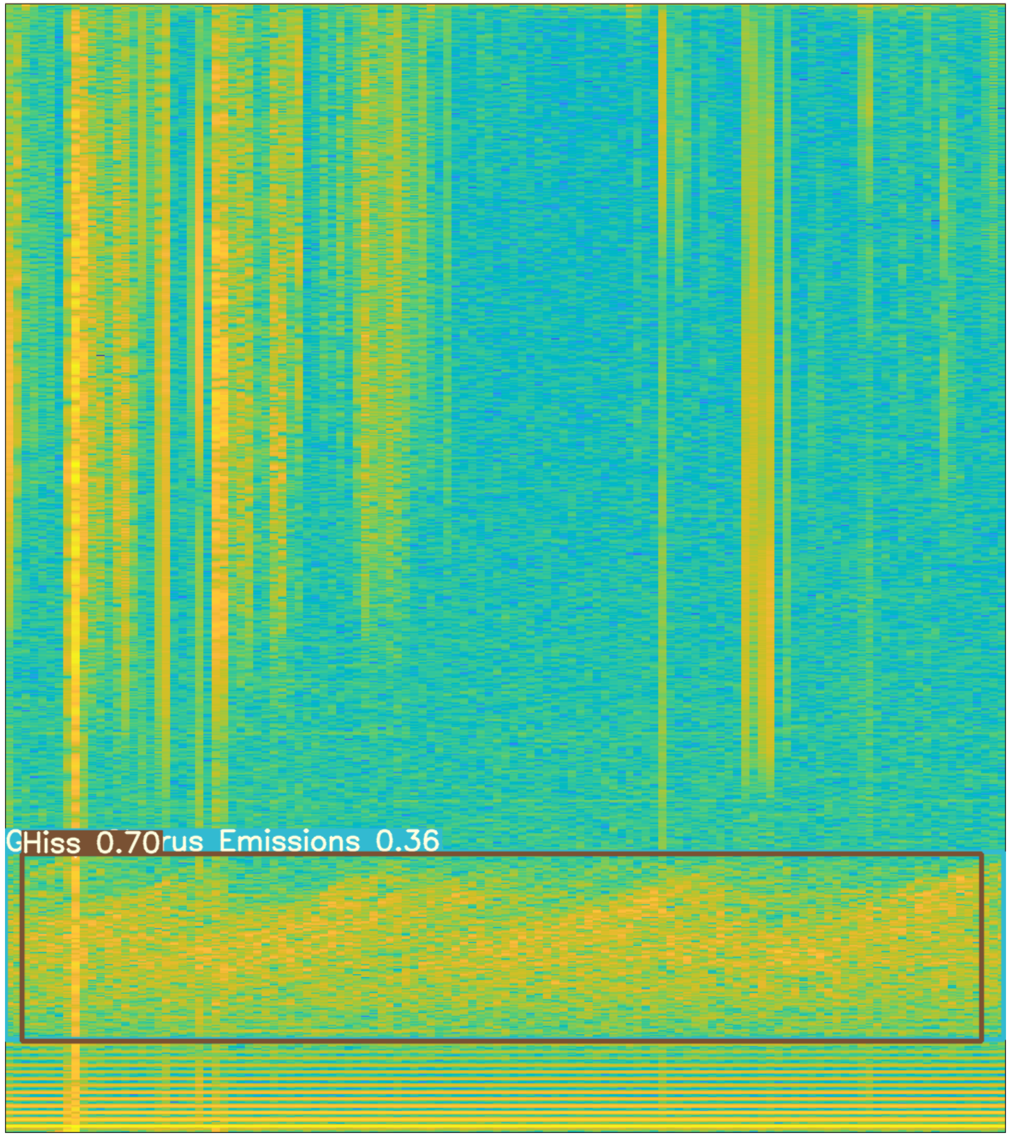

Future Work

- Extend machine learning models to other signal classes.

- Run ML models on spacecraft data (such as RBSP/Arase/MMS etc.).

- Begin larger collaborations using machine learning models for signal detection across the space physics community!

THANK YOU!

Questions?