Jet Propulsion Laboratory
California Institute of Technology

Optimizing Multiple Frequency-Shift Keying during Spacecraft Critical Events for Future Missions

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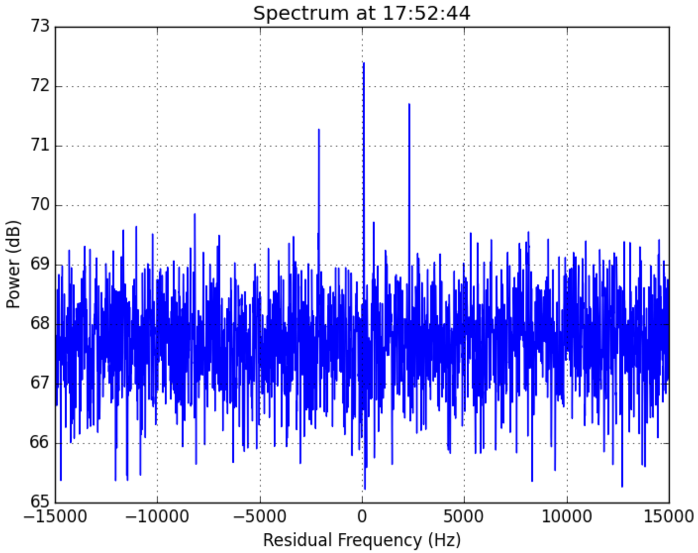
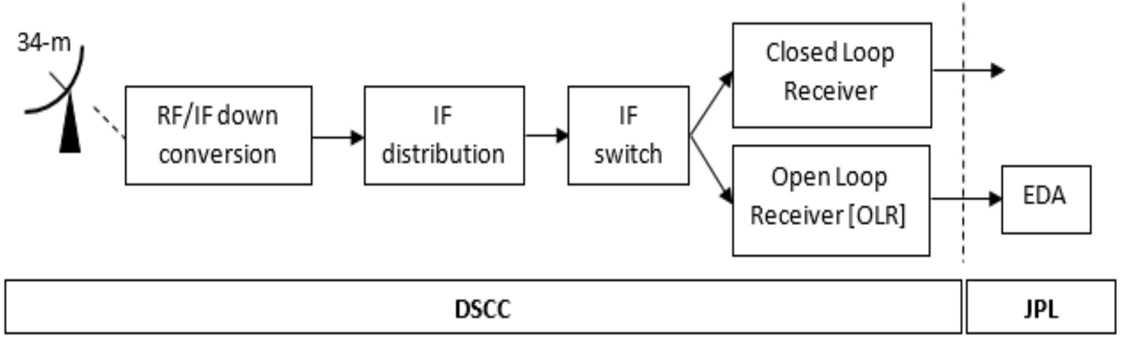
Background: What is Multiple Frequency Shift Keying?

- Carrier frequency at center (FFT)
- Data frequencies symmetric about the carrier
- Difference between data and carrier is a tone
- Use the word tone to mean the data, have a tone dictionary that matches the data to a real life event



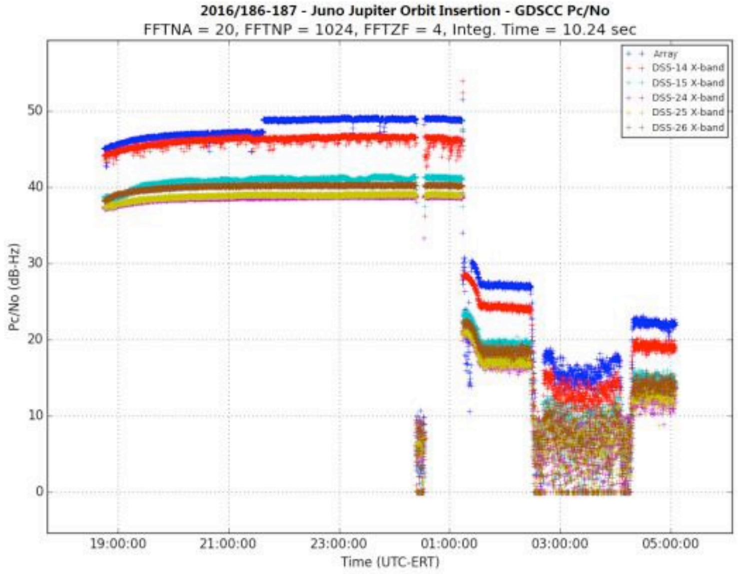
Background: How are tones received from spacecraft?



Deep Space Communications Complex: Goldstone, CA; Madrid, Spain; Canberra, Australia
RF/IF down conversion: Convert high frequencies to low frequencies
IF distribution: Signal amplification
IF switch: Split signal between receivers w/ multiple channels (here, only need OLRs)
Open Loop Receiver: Apply FFT, send raw data to EDA
Entry Descent and Landing Data Analysis: computer running software to identify tones, record and display results

Background: When have we used tones in the past?

- Missions: Mars Exploration Rovers, Mars Science Laboratory, Juno
- Use Cases: Entry Descent and Landing, Deep Space Maneuvers, Orbit Insertion
- Juno JOI Highlights
  - Goldstone – 4 34m + 70m, Array
  - Canberra – 3 34m + 70m
  - 70m at both complexes allowed >99% probability of correct tone detection
  - Any one 34m alone unable to meet 99%



Above: Pc/No vs Time for Juno JOI at Goldstone. Breaks represent switching between transmission antennas

Mean Pc/No between TLGA and 70m (DSS-14): 12.9 dB/Hz

Simulation: How do we choose a tone configuration?

Probability of correctly detecting a tone requires carrier acquisition and data-tone symbol detection:

$$P_{tone} = (P_{acq} \cdot P_{sym}) + \frac{1 - P_{acq}}{N_{sym}}$$

Need to set following parameters to meet mission P_{tone} requirements:

Search Space: (sampling rate)*(# Doppler rate pairs)/(FFT resolution)
N_{sym}: number of possible tone values
Non-coherent integration time: time spent integrating over signal
FFT bandwidth: inverse of coherent integration time
Modulation Index: angle from 0-90º, determines power split between carrier and data-tone

Simulation: What are some rules of thumb?

- Factor in expected Doppler dynamics via rules for Non-coherent integration time T and FFT bandwidth Δf

$$T < \sqrt{2\frac{\Delta f}{\ddot{f}_{max}}} \qquad \Delta f > \sqrt{4\dot{f}_{max}}$$

- Other Parameter Guidelines:
  - Search Space: high dynamics/low signal strength increases search space (low dynamics/high signal strength decreases search space)
  - N_{sym}: usually a power of two; max tones possible to define. 256 and 128 used in the past (smaller number actually defined).
  - Modulation Index: usually around 45º to split power between carrier and data tone evenly

Simulation: How should we split up use case analysis?

Dynamics:
Where are we going, and how are we getting there?

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Signal Strength:
What antennas are we using on the spacecraft and on the ground?

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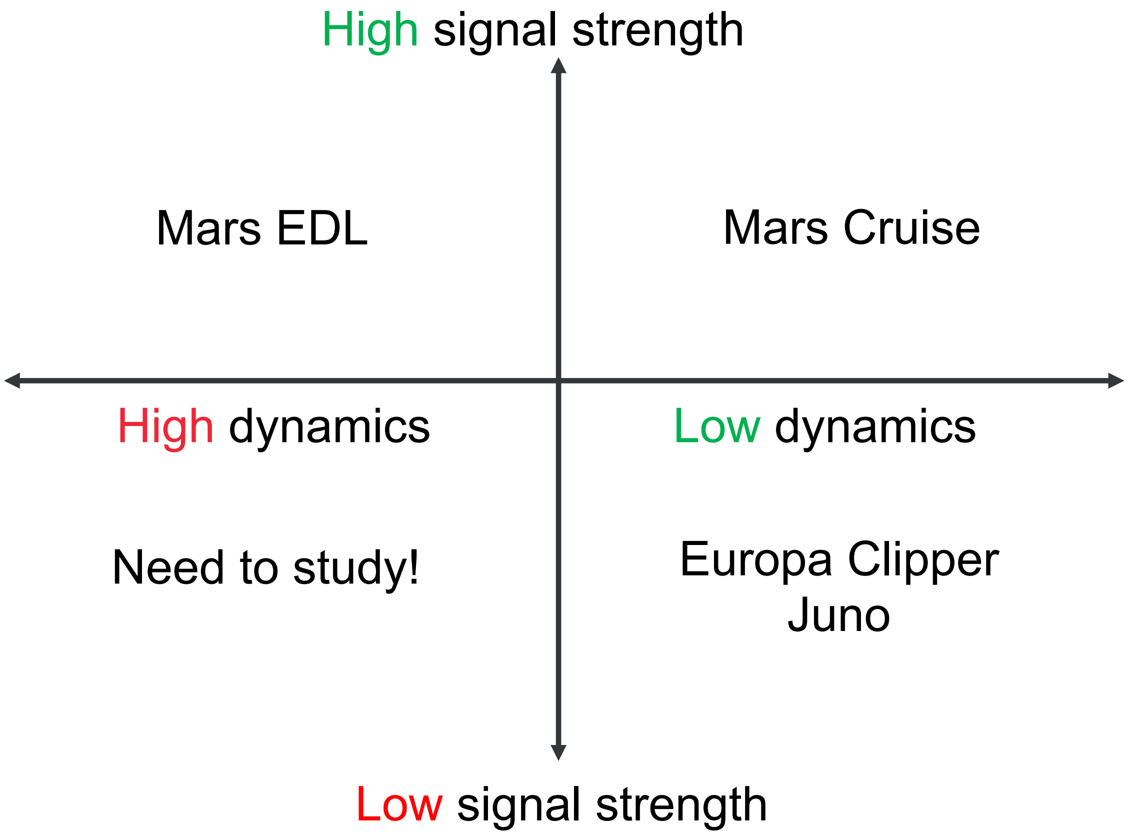
Determines:
the approximations we are allowed to make in simulation



Application: What do we expect for Europa Clipper?

Europa Clipper Mission: radar science for ice thickness, cameras/spectrometers for imaging, magnetometer for ocean salinity and depth

P_{tone} requirement for fault protection and JOI: 99% probability of detection on one 34m antenna

- Minimum Pc/No is 8 dB/Hz! (worst case in fault protection mode)
- Despite communication similarities with Juno mission, need to prepare for even lower signal strengths

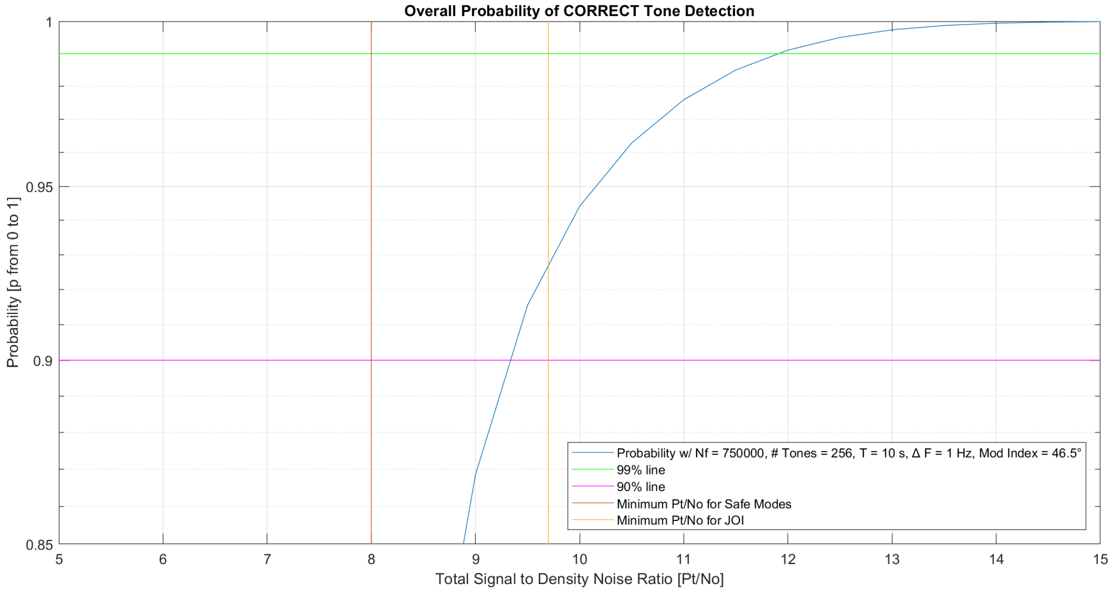
Application: What parameters did we use for Juno?

Parameter	Description	Juno JOI
Sampling Rate, $\boldsymbol{F_S}$	Number of samples/sec	50 kHz
$\boldsymbol{N_{FFT}}$	Number of samples/FFT, number of frequency bins searched	10k
FFT Bandwidth, $\boldsymbol{\Delta f}$	$\Delta f = F_S/N_{FFT}$	50 kHz / 10k = 5 Hz
Doppler rate pairs, $\boldsymbol{N_r}$	Number of Doppler rates searched	15
Search space, $\boldsymbol{N_f}$	Carrier: frequency-frequency rate search space searched, $N_f = N_{FFT} * N_r$	Carrier: 150k
# Tones	Number of tones possible to define	256
(Non-coherent) Integration time, $\boldsymbol{T}$	Amount of time integrating over signal	3 s
Modulation Index, Δ	Angle in degrees for carrier modulation	46.5

Application: What configuration do we try for Clipper?

Parameter	Description	Juno JOI	Europa Clipper
Sampling Rate, $\boldsymbol{F_S}$	Number of samples/sec	50 kHz	50 kHz
$\boldsymbol{N_{FFT}}$	Number of samples/FFT, number of frequency bins searched	10k	**50k**
FFT Bandwidth, $\boldsymbol{\Delta f}$	$\Delta f = F_S/N_{FFT}$	50 kHz / 10k = 5 Hz	50 kHz / 50k = **1 Hz**
Doppler rate pairs, $\boldsymbol{N_r}$	Number of Doppler rates searched	15	15
Search space, $\boldsymbol{N_f}$	Carrier: frequency-frequency rate search space searched, $N_f = N_{FFT} * N_r$	Carrier: 150k	**Carrier: 750k**
# Tones	Number of tones possible to define	256	256
(Non-coherent) Integration time, $\boldsymbol{T}$	Amount of time integrating over signal	3 s	**10 s**
Modulation Index, Δ	Angle in degrees for carrier modulation	46.5	**46.5**

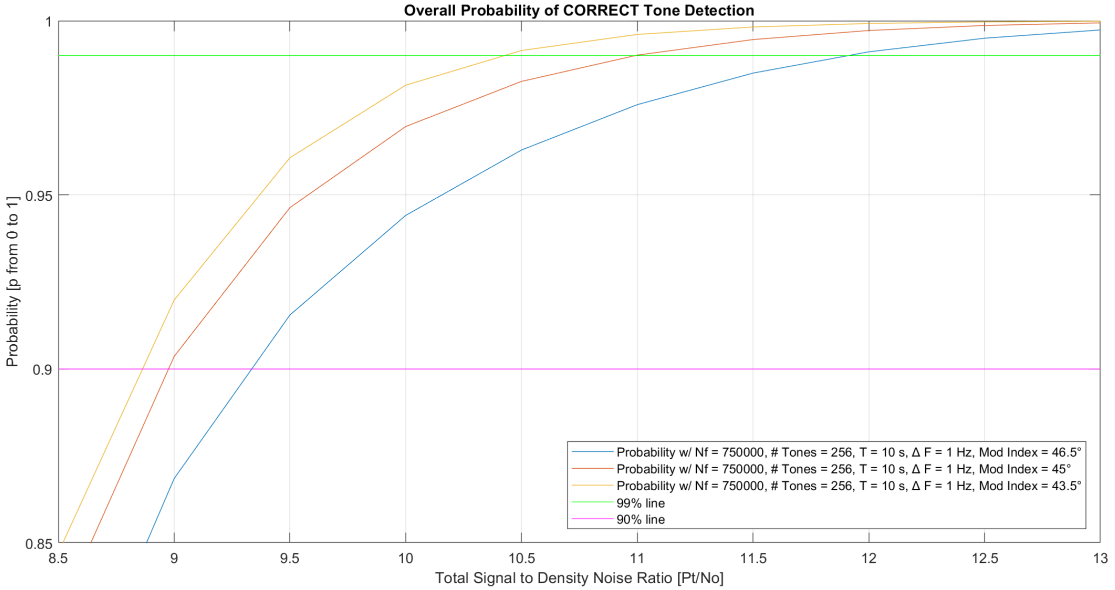
Application: What configuration do we try for Clipper?



Parameter	Juno JOI	Europa Clipper
Sampling Rate, F_S	50 kHz	50 kHz
N_{FFT}	10k	**50k**
FFT Bandwidth, Δf	50 kHz / 10k = 5 Hz	50 kHz / 50k = **1 Hz**
Doppler rate pairs, N_r	15	15
Search space, N_f	Carrier: 150k	**Carrier: 750k**
# Tones	256	256
(Non-coherent) Integration time, T	3 s	**10 s**
Modulation Index, Δ	46.5	**46.5**

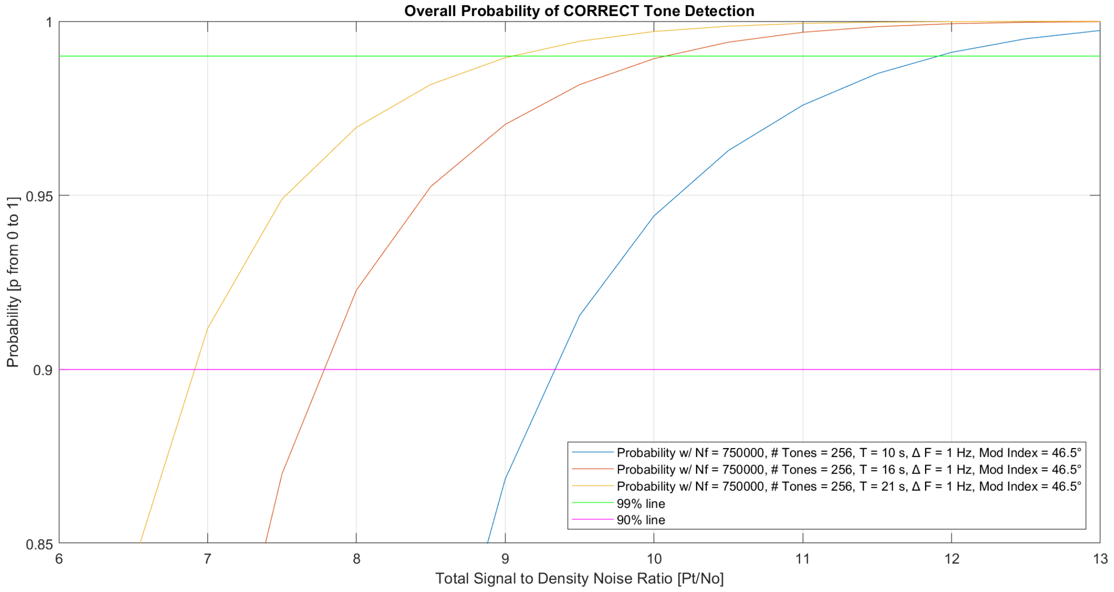
Critical Parameters

Application: What effect does modulation index have?



- Modulation index determines ratio of power in carrier versus data tone
- By reducing angle, more power in carrier

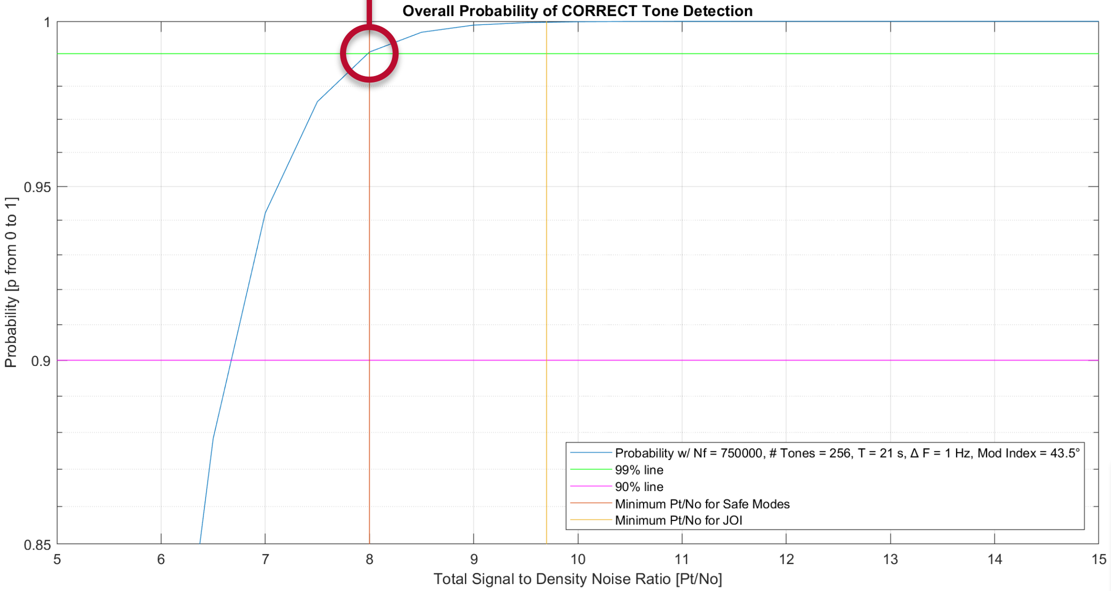
Application: What about non-coherent integration time?



- Increasing the tone length
- More unlikely that noise will persist for long enough to be mistaken for a data-tone
- Assuming low Doppler acceleration

Application: What are the current Clipper parameters?

Meeting the Requirement!



Parameter	Juno JOI	Europa Clipper
Sampling Rate, F_S	50 kHz	50 kHz
N_{FFT}	10k	**50k**
FFT Bandwidth, Δf	50 kHz / 10k = 5 Hz	50 kHz / 50k = **1 Hz**
Doppler rate pairs, N_r	15	15
Search space, N_f	Carrier: 150k	**Carrier: 750k**
# Tones	256	256
(Non-coherent) Integration time, T	3 s	**21 s**
Modulation Index, Δ	46.5	**43.5**

10 s → 21 s, 46.5º → 43.5º

Future Work: What should we do next?

- Study the high dynamics low signal strength case
    - Mars missions covered high/low dynamics with high signal strength
    - Clipper is low dynamics high signal strength
    - This is the final, most difficult case left
- Potential use case: Deorbit, descent, and landing onto a planetary body, perhaps want to land on Europa in the future?

Acknowledgements: Who helped you?

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Questions?: [your question here!]

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