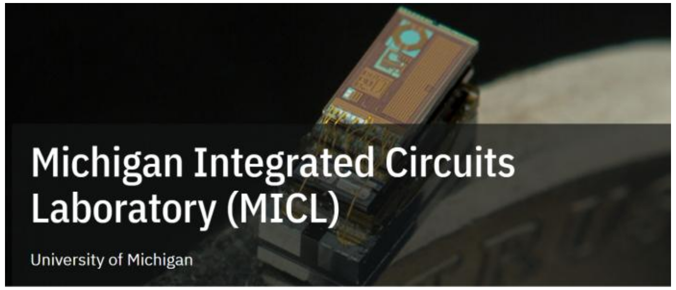
Global Localization of Energy-Constrained Miniature RF Emitters using Low Earth Orbit Satellites

Yunfan Wang, Steve Young, **Demba Komma,** Jaechan Lim, Zhen Feng,
Zichen Fan, Chien-wei Tseng, Hun-Seok Kim, and David Blaauw



Michigan Integrated Circuits Laboratory (MICL)

University of Michigan

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Motivation

- **Daily and global tracking of ~cm objects is an important technique**
  - It enables many promising applications
    - Small animals (< 10 g) tracking
    - Long-term, inconspicuous safeguarding of valuable asset

Monarchs butterfly

Bee hummingbird

Art works

Existing localization approaches

- It is challenging for existing localization approaches to achieve this goal

GPS tag

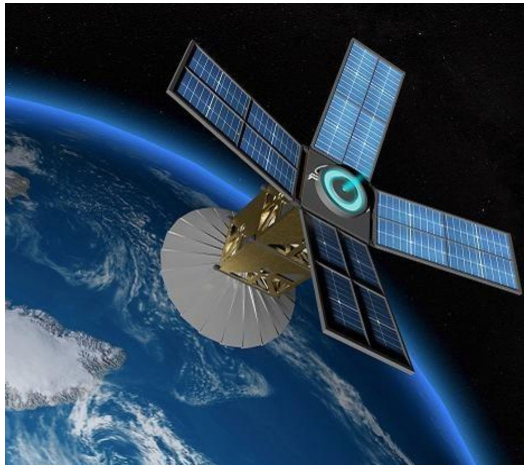
- cm size
- Global tracking
- Tracker retrieval required

Motus

- cm size
- Tracker retrieval avoided
- Constrained coverage range

MSAIL

- cm size
- Global tracking
- Tracker retrieval required

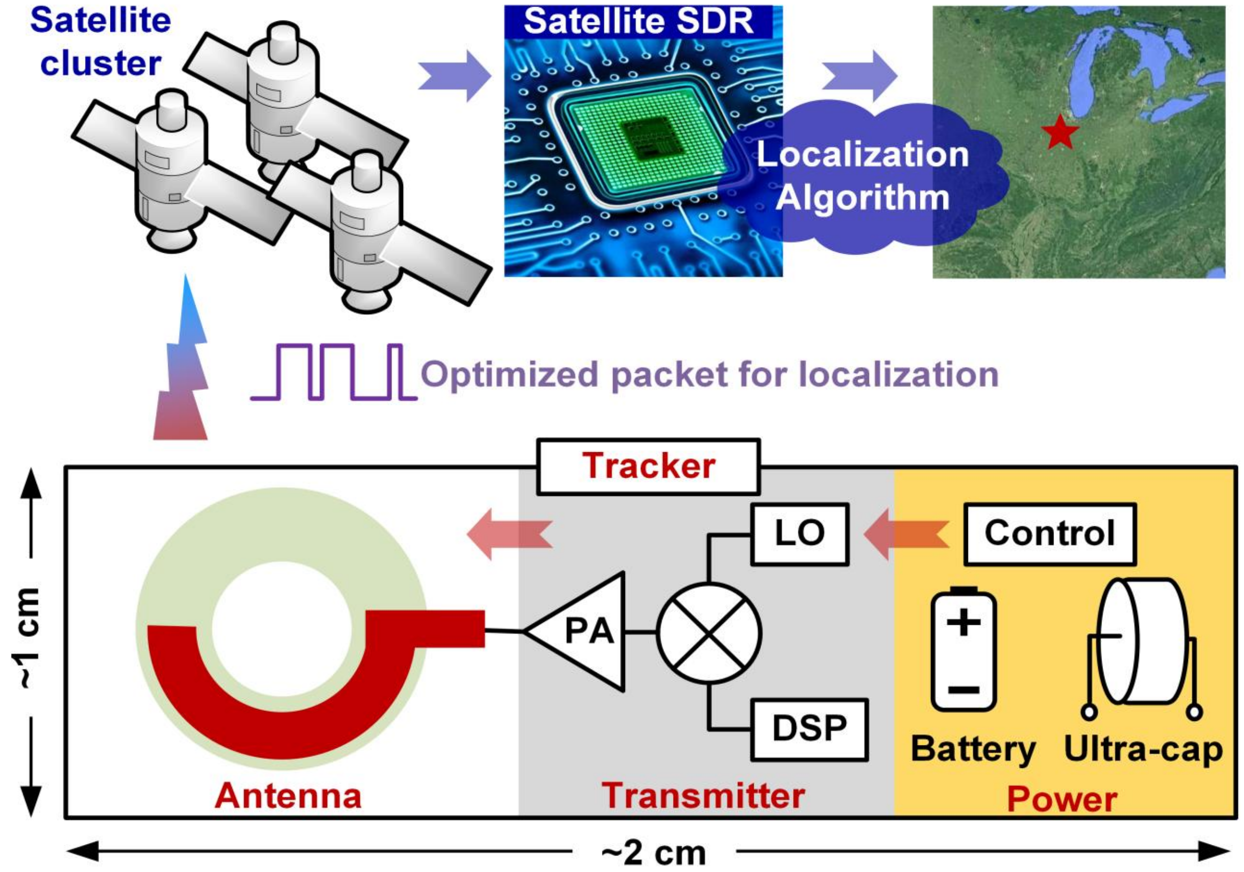


EOS

- Global tracking
- Tracker retrieval avoided
- Only tracks large objects

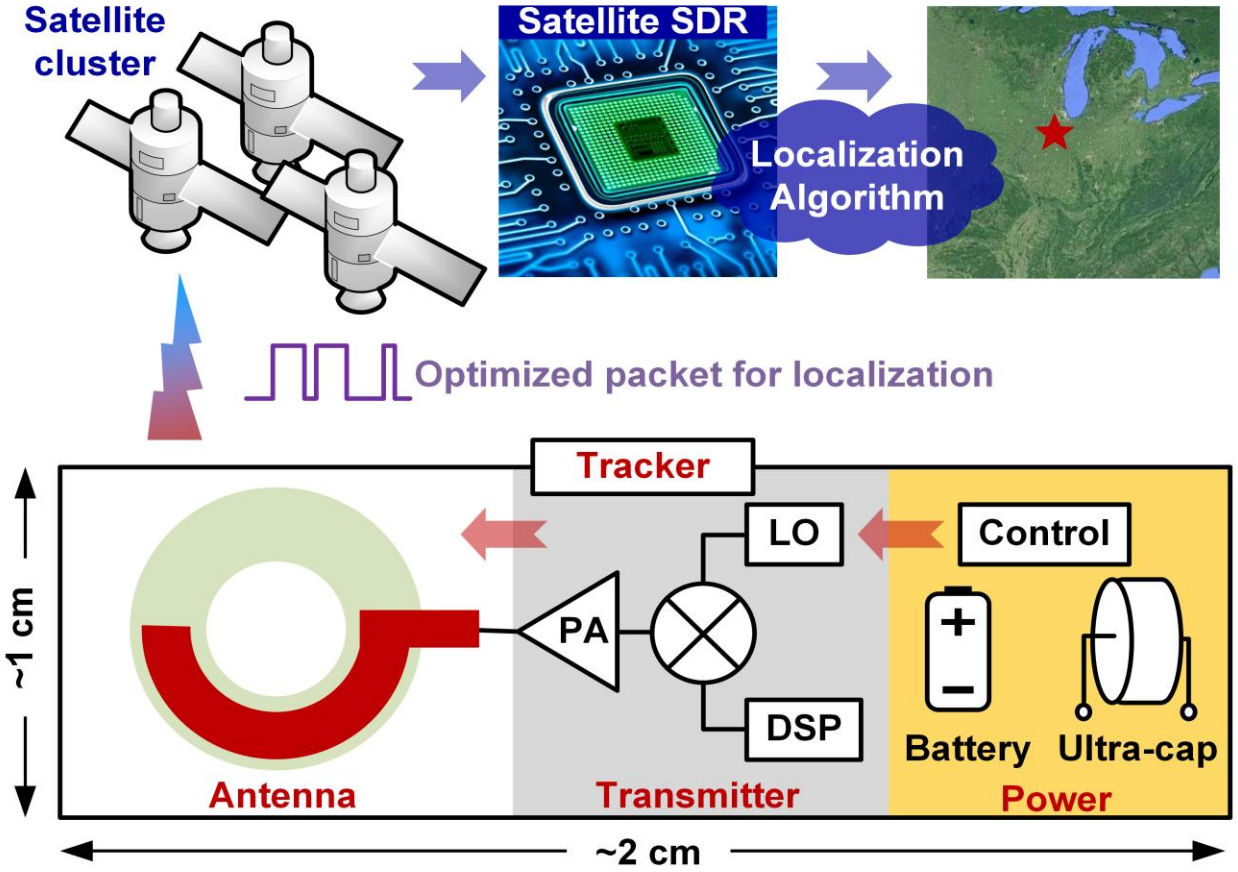
Proposed system based on LEO satellites

- **Proposed system**
  - Cm-size RF tracker for periodic packet transmission
  - Low earth orbit (LEO) satellites capture packet, followed by packet detection and localization
  - Optimized packet for localization



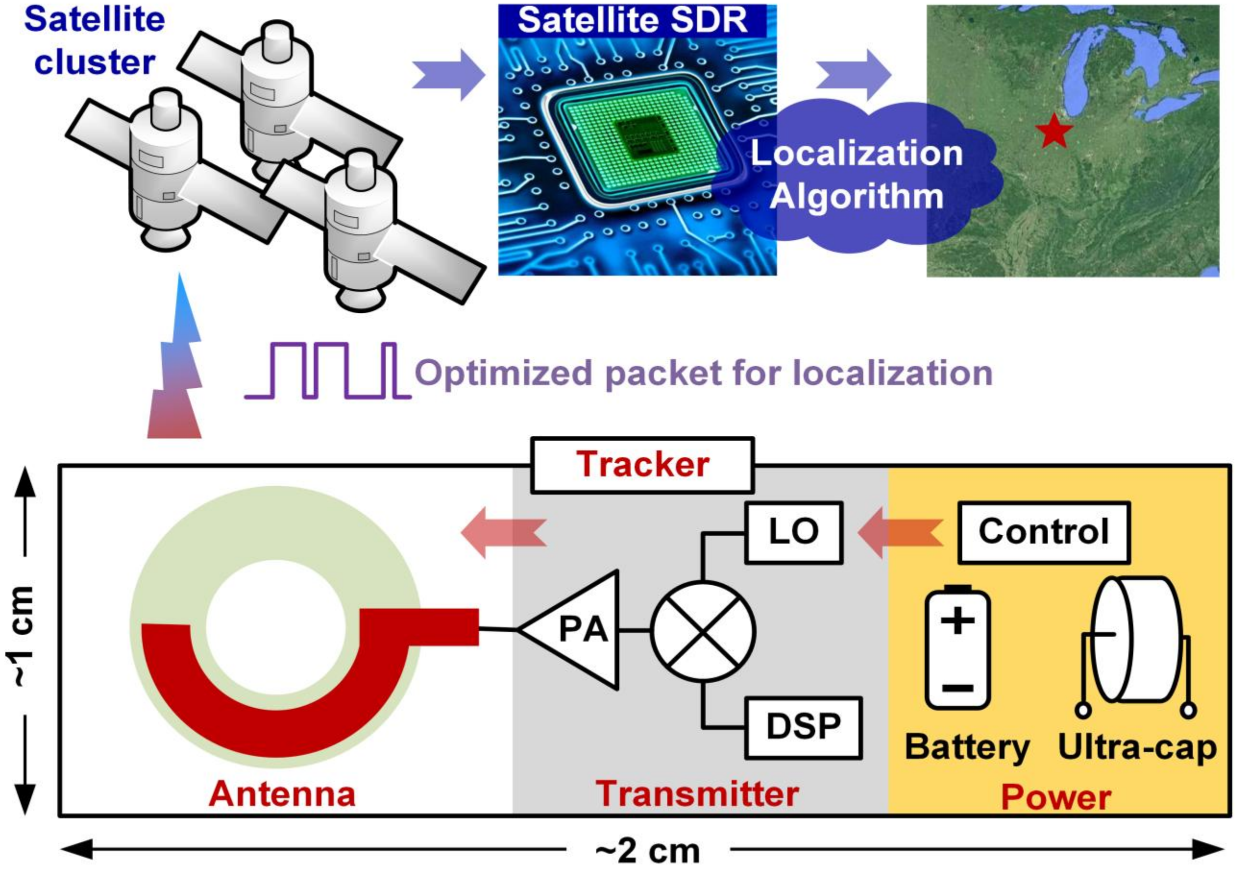
Proposed system based on LEO satellites

- **LEO satellite**
  - Low orbit height: 200 – 2000 km
  - Polar LEO satellites fly over the tracker anywhere on earth once per day
  - Localization based on received signal's time/frequency difference of arrival (TDoA/FDoA)



Proposed system based on LEO satellites

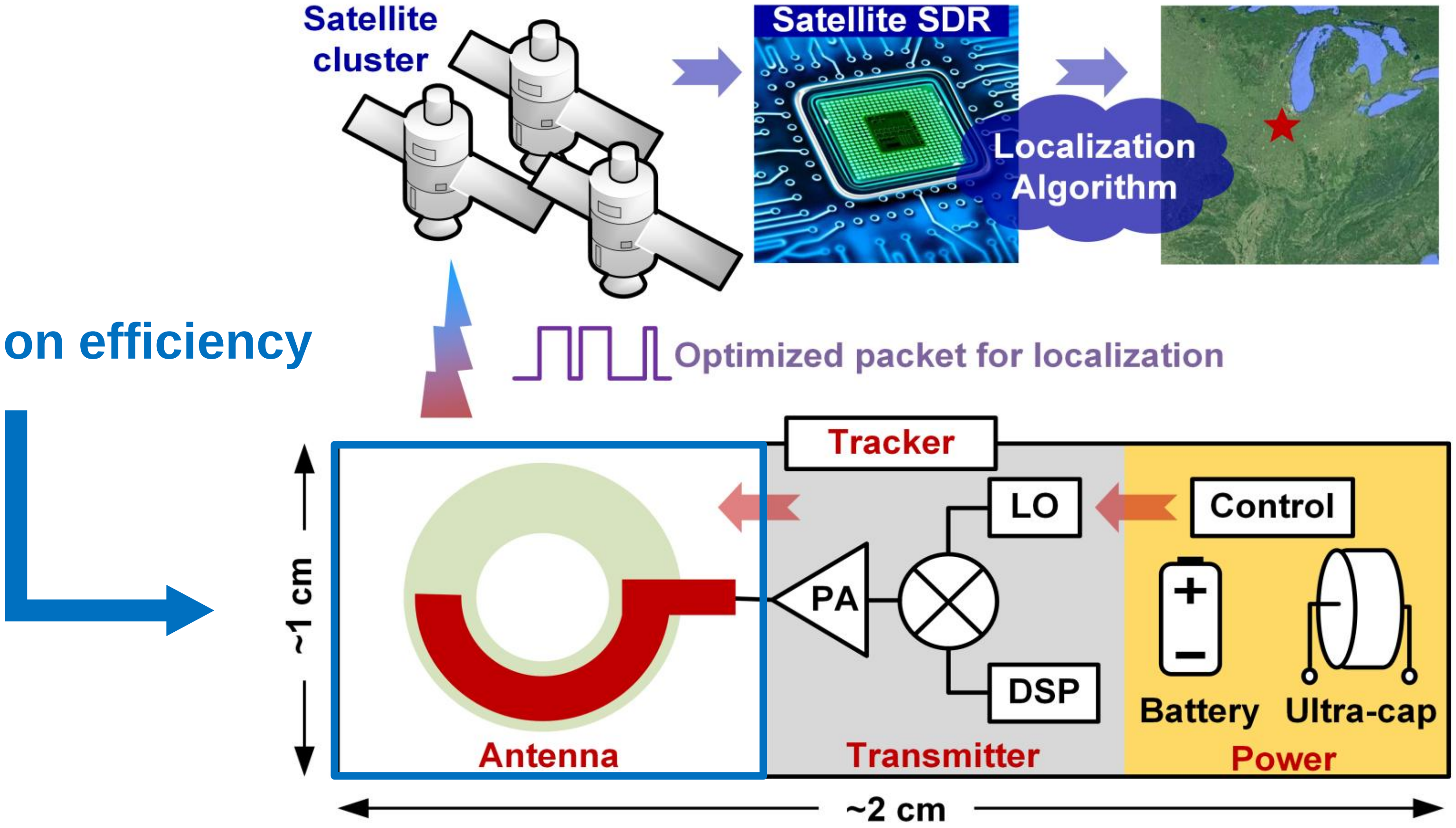
- **LEO satellites present three advantages over existing approaches**
  - Tracker retrieval unnecessary
  - Enables global tracking
  - Miniaturization to cm-size is feasible – topic of this paper



Challenges due to cm-size constraint

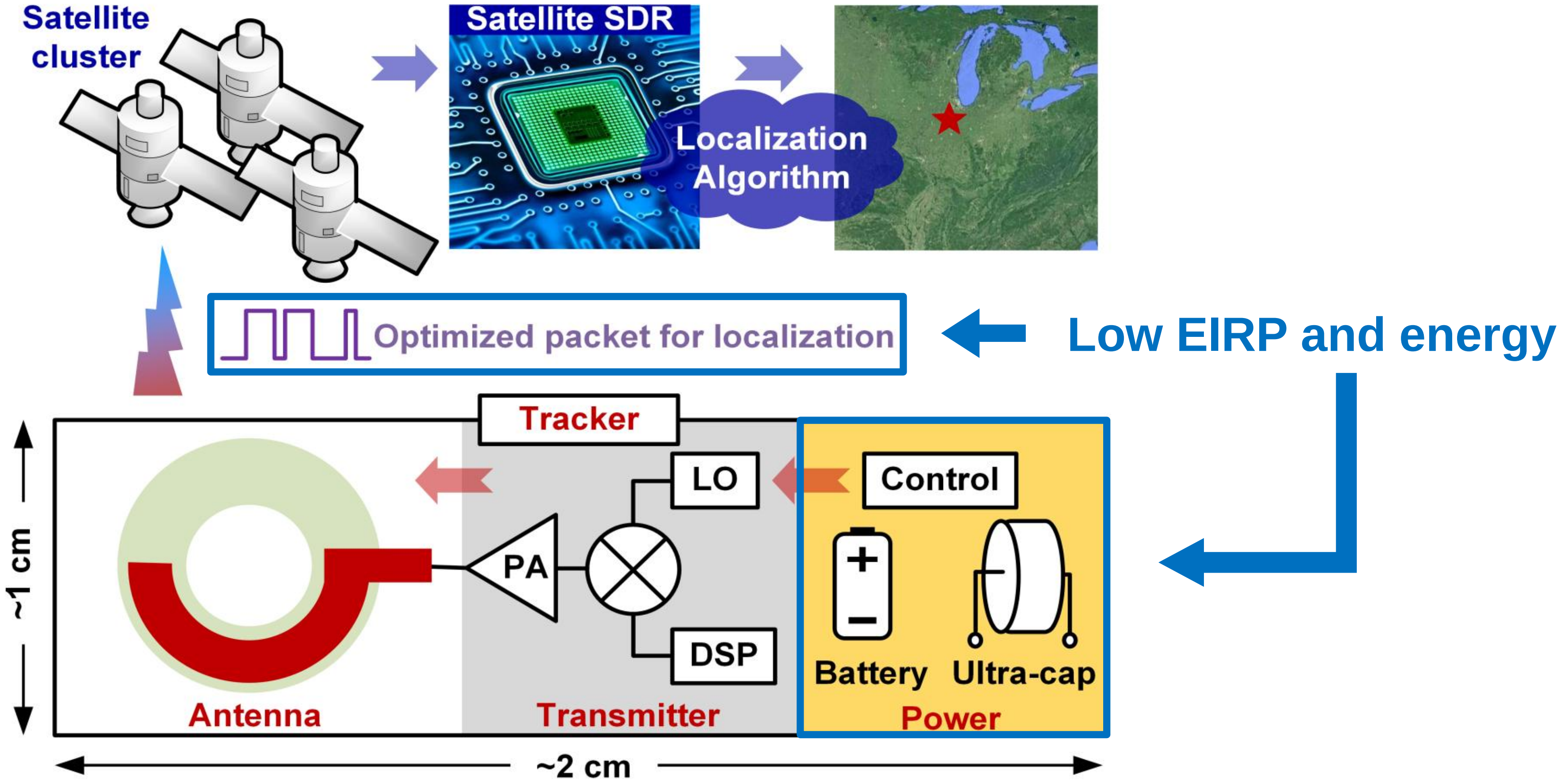
- **Challenge 1: Low radiation efficiency of electrical small antenna and high path loss**
  - Solutions: frequency selection and customized antenna to maximize received power
  - Results: 2.946 GHz operation frequency and 65% radiation efficiency

Low radiation efficiency



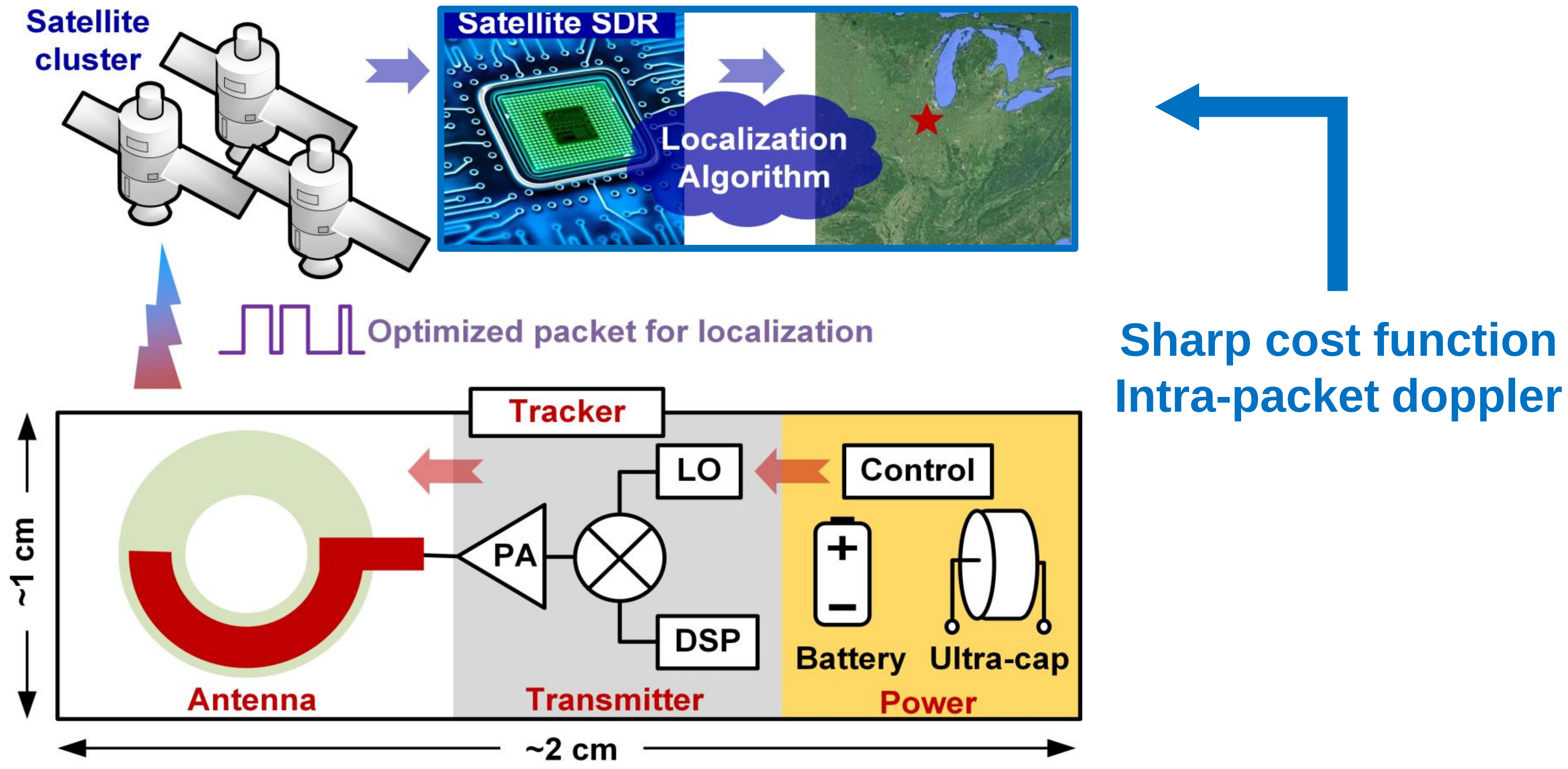
Challenges due to cm-size constraint

- **Challenge 2: Limited EIRP and energy due to *low instantaneous current* and battery capacity**
  - Solutions: waveform optimization to maximize localization accuracy
  - Results: *120-ms* and 50 kHz BPSK sequence with 23-dBm EIRP and 60-s interval



Challenges due to cm-size constraint

- **Challenge 3: Sharp cost function and intra-packet Doppler drift due to long packet length**
  - Solutions: Localization based on TDoA error maps and intra-packet Doppler calibration
  - Results: 1000x computation cost reduction and 3x localization accuracy enhancement



Sharp cost function
Intra-packet doppler

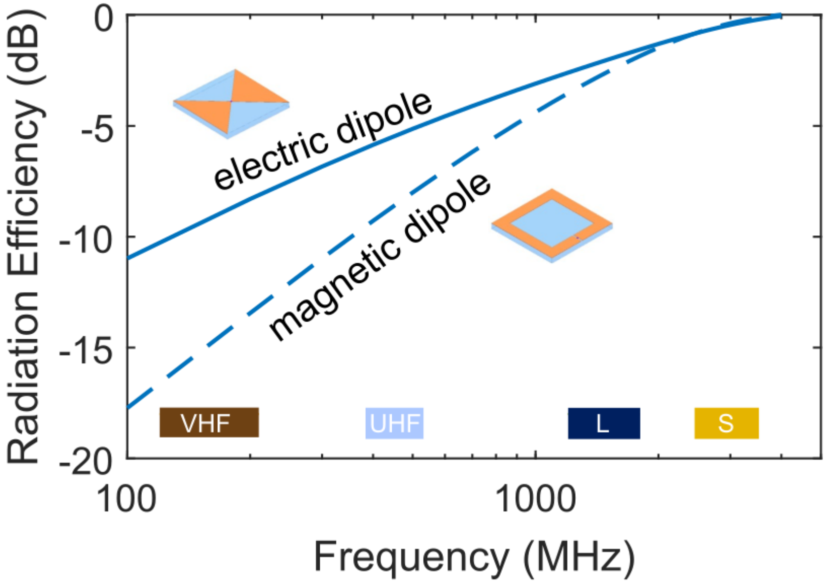
Frequency selection and customized antenna

Constraints

- We were free to choose operating frequency among available satellite reception bands
- The tracker antenna footprint was limited to **1 cm x 1 cm** (electrically-small in all bands)
- We assumed no control over tracker orientation after deployment: low-gain, omni-directional radiation patterns are better to maximize detection probability

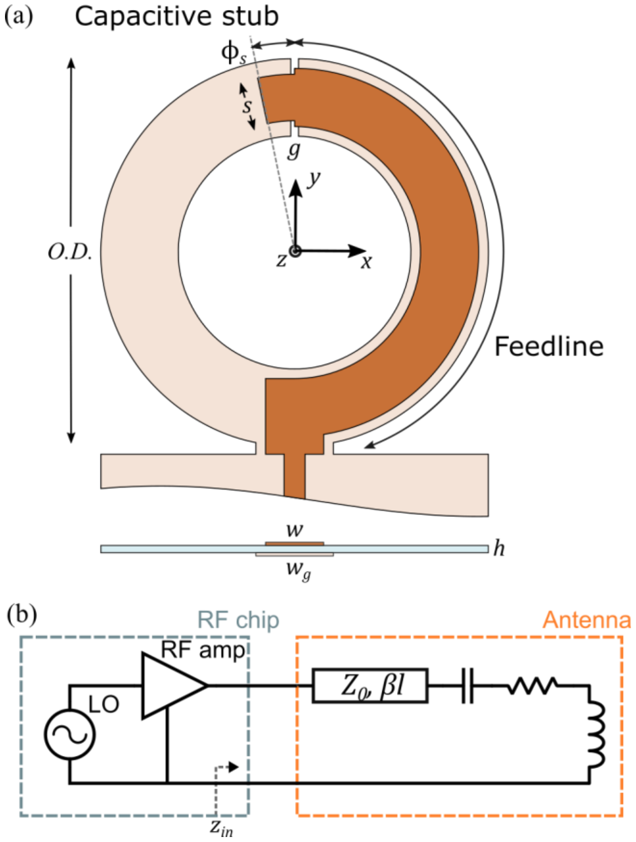
Frequency tradeoffs

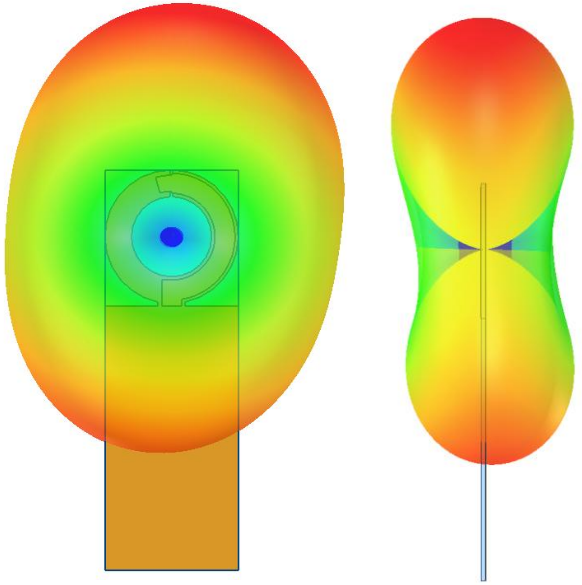
- Lower frequencies have smaller free-space path loss (scaling with λ^{-2})
- Lower frequencies have *much worse* radiation efficiency (scaling with λ^{-4})
- Electrically-small antennas also have narrower bandwidth and more challenging impedance matching



Frequency selection and customized antenna

- **Custom antenna design**
  - Self-resonant loop with integrated impedance matching
  - 1 cm x 1 cm footprint
  - Operating frequency in S-band (2.946 GHz)
  - 20 MHz bandwidth
  - 65% radiation efficiency
  - 1 dB peak gain





Waveform optimization

- **Constraints**
  - **Transmitter bandwidth is limited by satellite receiver capability**
  - Tracker's energy is bound by battery capacity, supply voltage and DC-to-RF efficiency

- **Modulation type and modulation rate ($\boldsymbol{B_s}$)**
  - Modulation type has negligible impact on localization accuracy
    - BPSK is suitable for coherent packet detection
  - Larger modulation rate (B_s) provides better time resolution (scaling with ${B_s}^{-1}$)
    - Maximum modulation rate (50 kHz) is set by receiver's bandwidth

$$\underbrace{2\mathrm{D_c}}_{\text{Doppler ranges}} + \underbrace{2\mathrm{B_s}}_{\text{Signal's bandwidth}} = \underbrace{\mathrm{f_s}/2}_{\text{DC-Edge of receiver}}$$

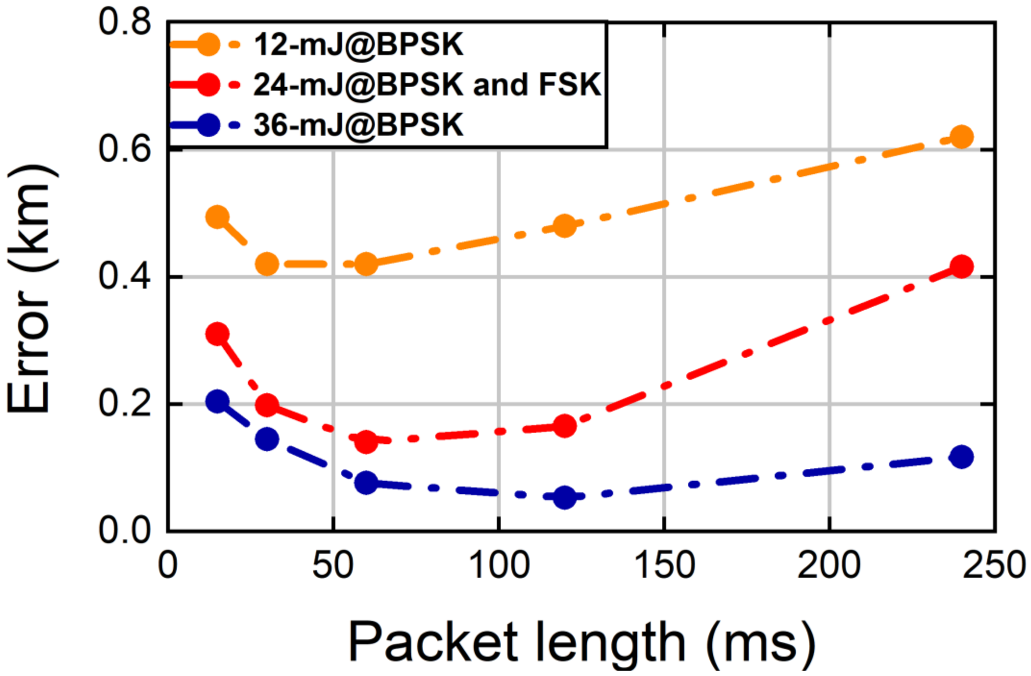
(2 x 75 kHz) (2 x 50 kHz) (500/2 kHz)

Waveform optimization

- **Constraints**
  - Transmitter bandwidth is limited by satellite receiver capability
  - **Tracker's energy is bound by battery capacity, supply voltage and DC-to-RF efficiency**

- **Packet length (τ) tradeoffs**
  - Larger $\boldsymbol{\tau}$ enables better frequency resolution (scaling with τ^{-1})
  - Larger $\boldsymbol{\tau}$ introduces more noise in cost function (scaling with τ)

- **Optimal packet length**
  - 120-ms based on single packet localization

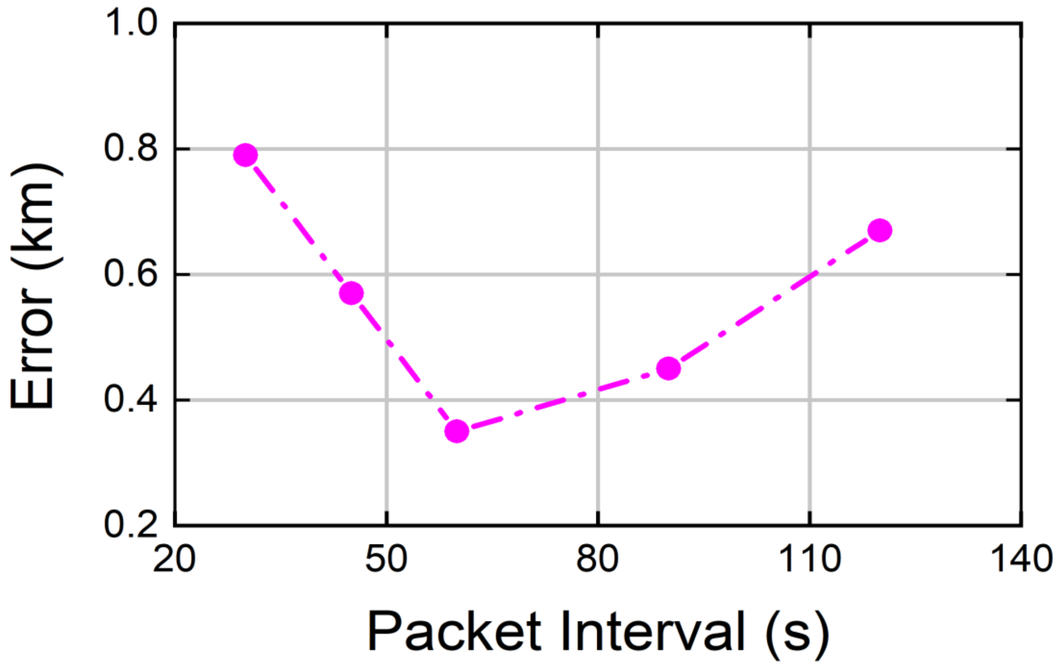


Waveform optimization

- **Constraints**
  - Transmitter bandwidth is limited by satellite receiver capability
  - **Tracker's energy is bound by battery capacity, supply voltage and DC-to-RF efficiency**

- **Packet interval (T) tradeoffs**
  - Larger T enables larger single packet energy (scaling with T)
  - Larger T results in fewer packets captured (scaling with T^{-1})

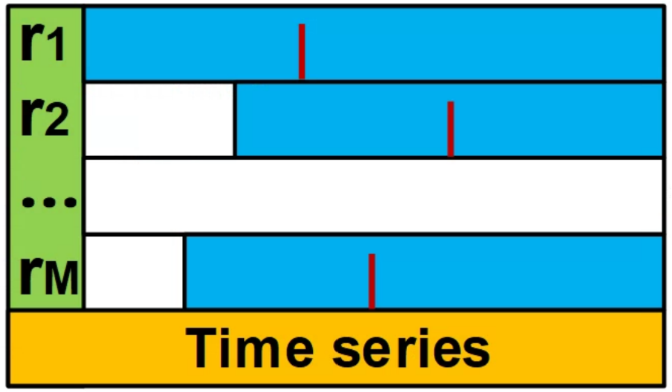
- **Optimal packet interval**
  - 60-s based on multi packet localization



Localization based on TDoA error maps

- **Conventional coarse localization approach**
  - Direct position calculation using TDoA has high localization error due to weak packets
  - Grid search with large spacing is not effective with sharp cost function of long packet

- **Proposed coarse localization approach**
  - Calculation of error between observed and estimated TDoA
    - Observed TDoA: Based on time indexes in packet detection



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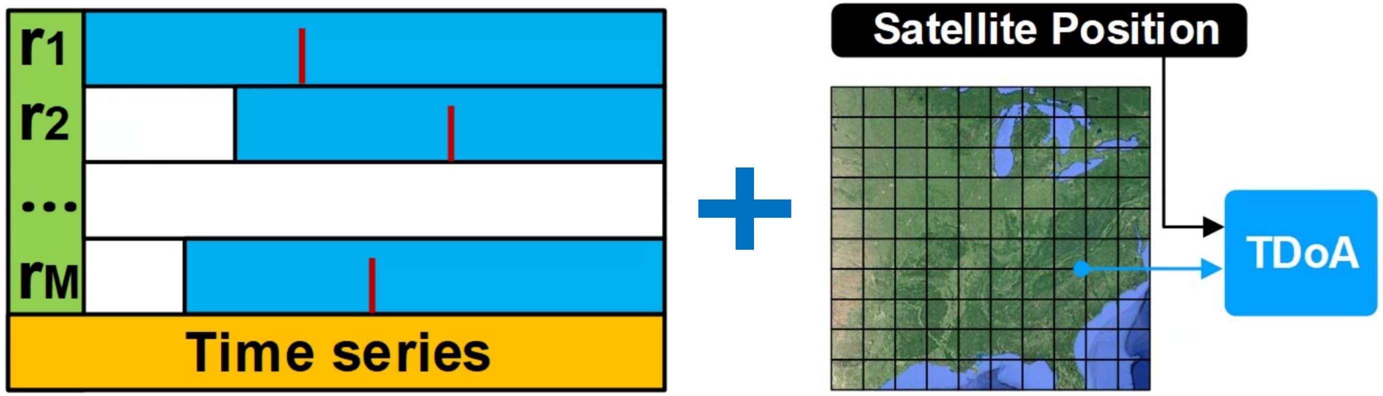
- **Proposed coarse localization approach**
  - Calculation of error between observed and estimated TDoA
    - Observed TDoA: Based on time indexes in packet detection
    - Estimated TDoA: Based on distance between satellites and tracker



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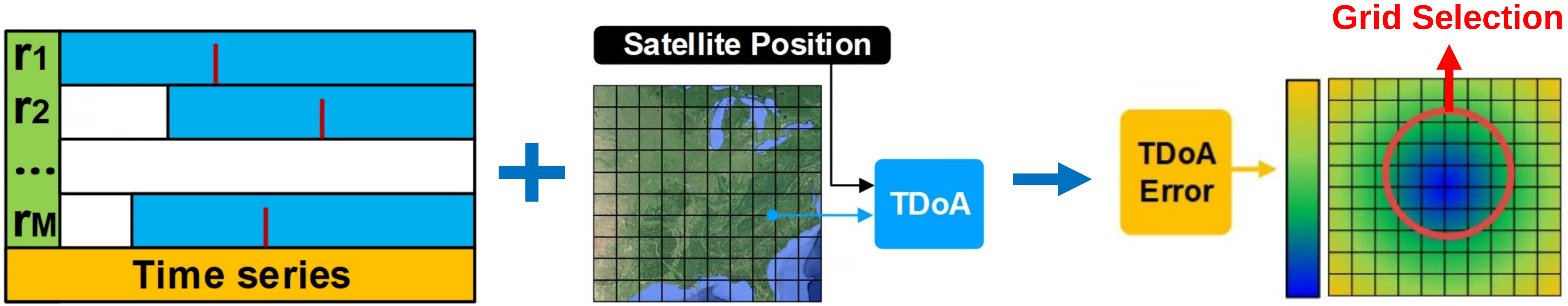
- **Proposed coarse localization approach**
  - Calculation of error between observed and estimated TDoA
    - Observed TDoA: Based on time indexes in packet detection
    - Estimated TDoA: Based on distance between satellites and tracker
    - TDoA error calculation and grid selection

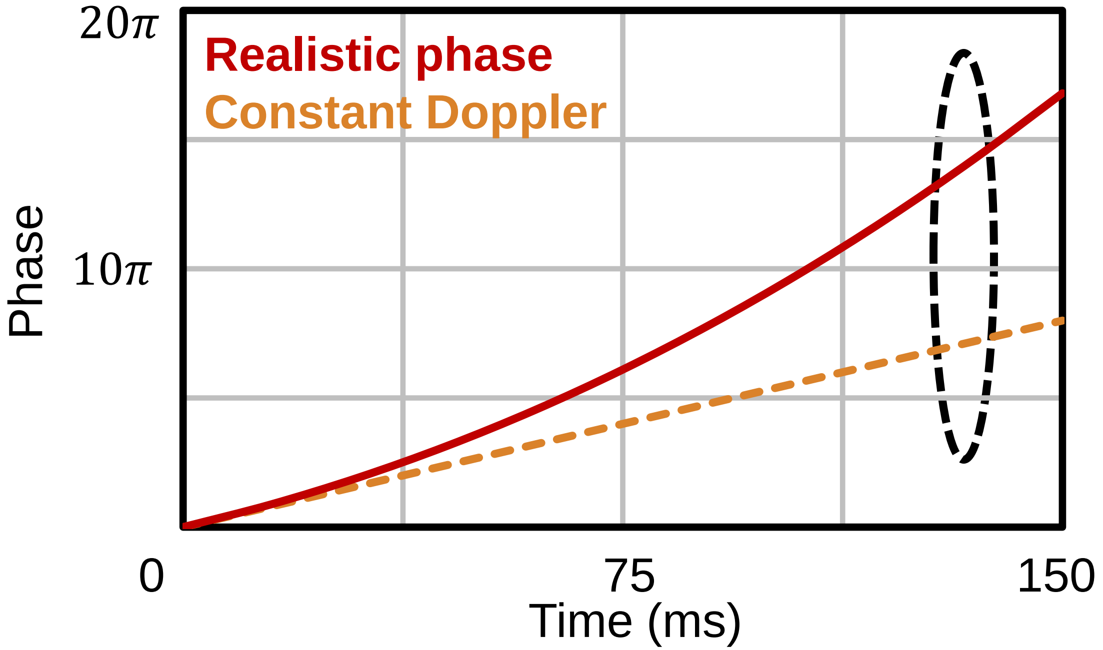


Intra-packet Doppler calibration

- **Constraint**
  - Adequate single packet energy ($EIRP \cdot \tau$) for packet detection
  - Low EIRP results in long packets (e.g., 120 ms)

- **Conventional model**
  - Received signal with constant Doppler (f)

$$R(t) = s(t - \tau)e^{-j2\pi ft} + n(t)$$



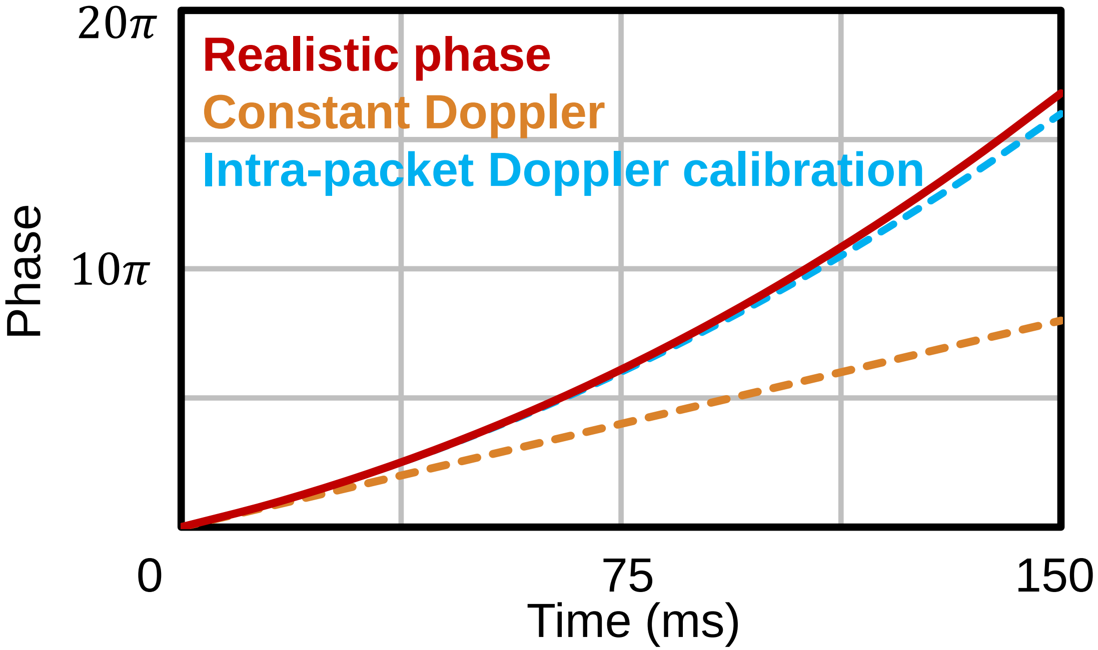
Not established for long packet

Intra-packet Doppler calibration

- **Constraint**
  - Adequate single packet energy ($EIRP \cdot \tau$) for packet detection
  - Low EIRP results in long packets (e.g., 120 ms)

- **Proposed model**
  - Received signal with linear intra-packet Doppler calibration (d)

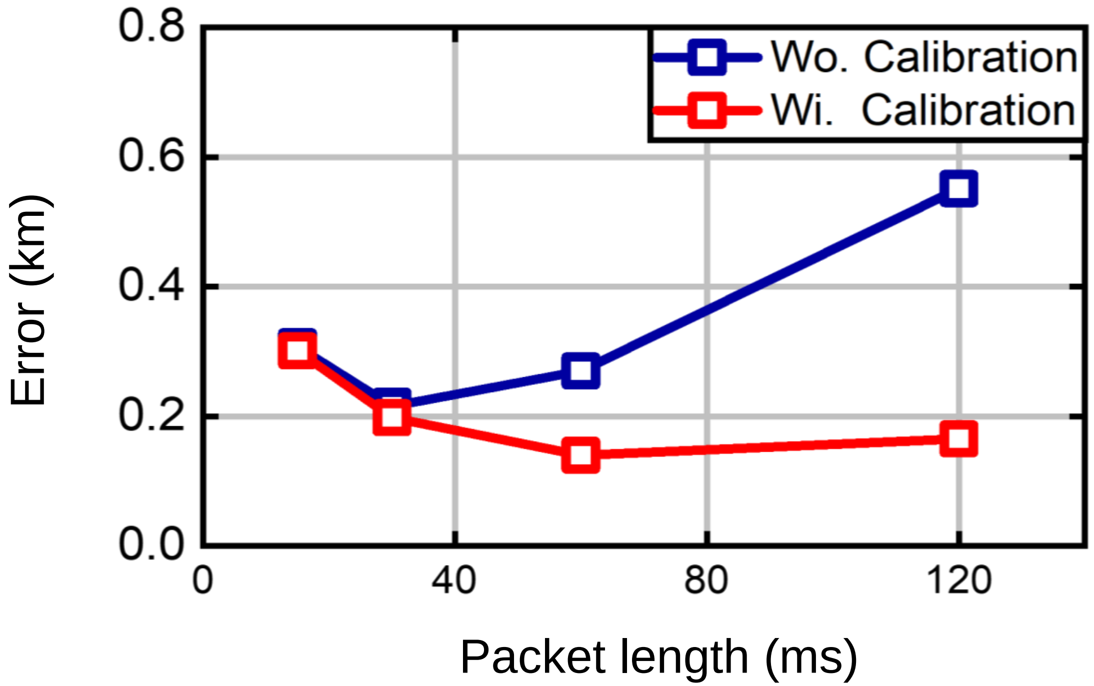
$$R(t) = s(t-\tau)e^{-j2\pi ft}\mathbf{e^{j\pi dt^2}} + n(t)$$



Intra-packet Doppler calibration

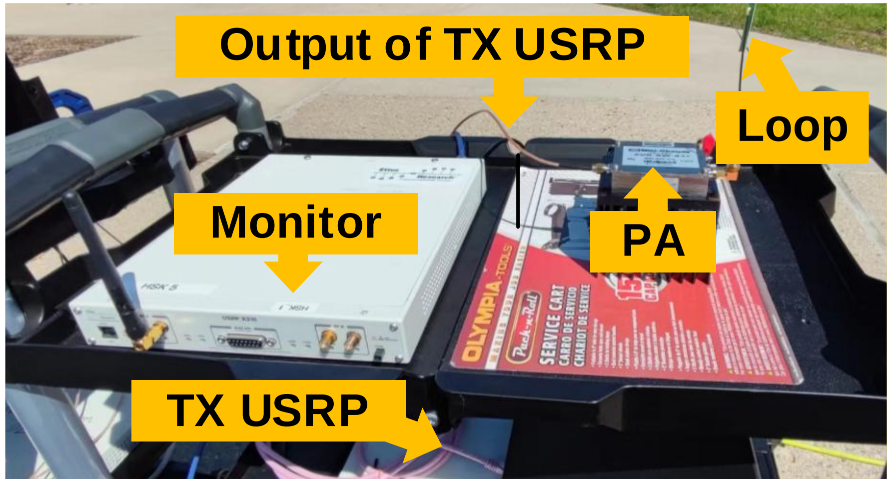
- **Constraint**
  - Adequate single packet energy ($EIRP \cdot \tau$) for packet detection
  - Low EIRP results in long packets (e.g., 120 ms)

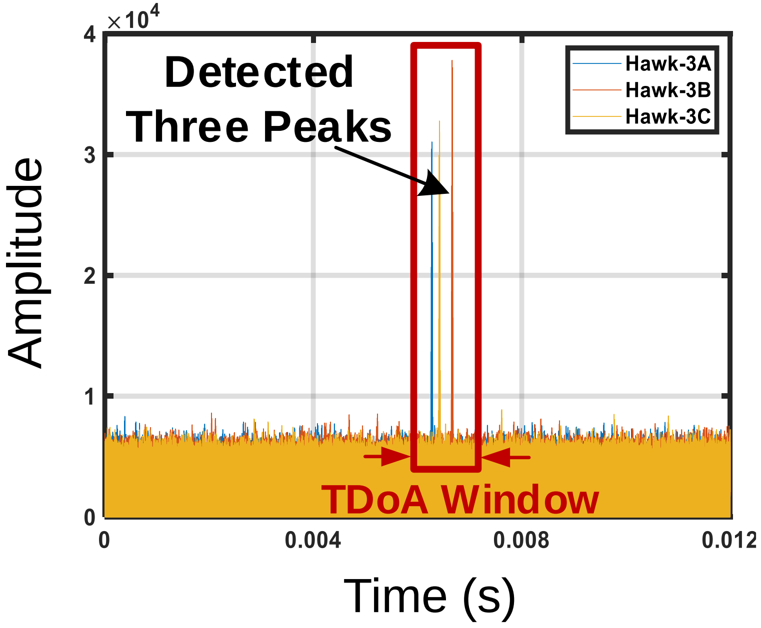
- **Proposed model**
  - Based on single-packet localization simulation, it enhances localization accuracy by **3 X**



Real-World experiments

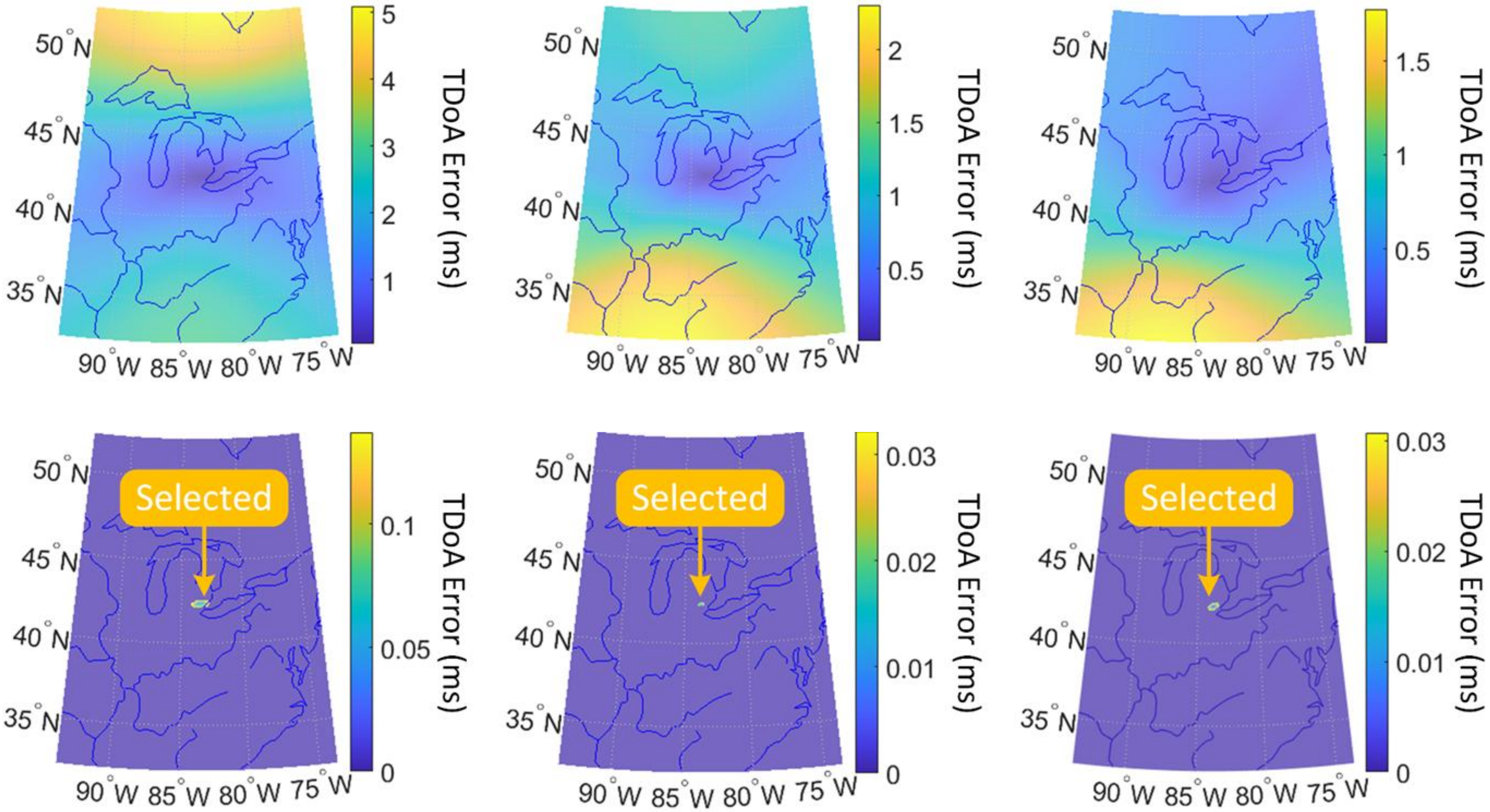
- **Real-world experiments were carried out at three satellite elevations**
  - Overhead (85 degrees), medium (75 degrees), and low (58 degrees) elevation
  - Tx setup
    - Tx USRP + PA + loop antenna: transmit **optimized BPSK packet**
    - Monitor: record packet transmission to confirm packet transmission
  - Packet detection on the satellites (example)
    - Prominent peaks (after correlation) can be observed on three satellites
    - Successful packet detection





Localization based on TDoA error maps

- **Results**
  - Example outputs for three elevation angles
  - Smooth merit over large areas
  - **~1000x** computation cost reduction



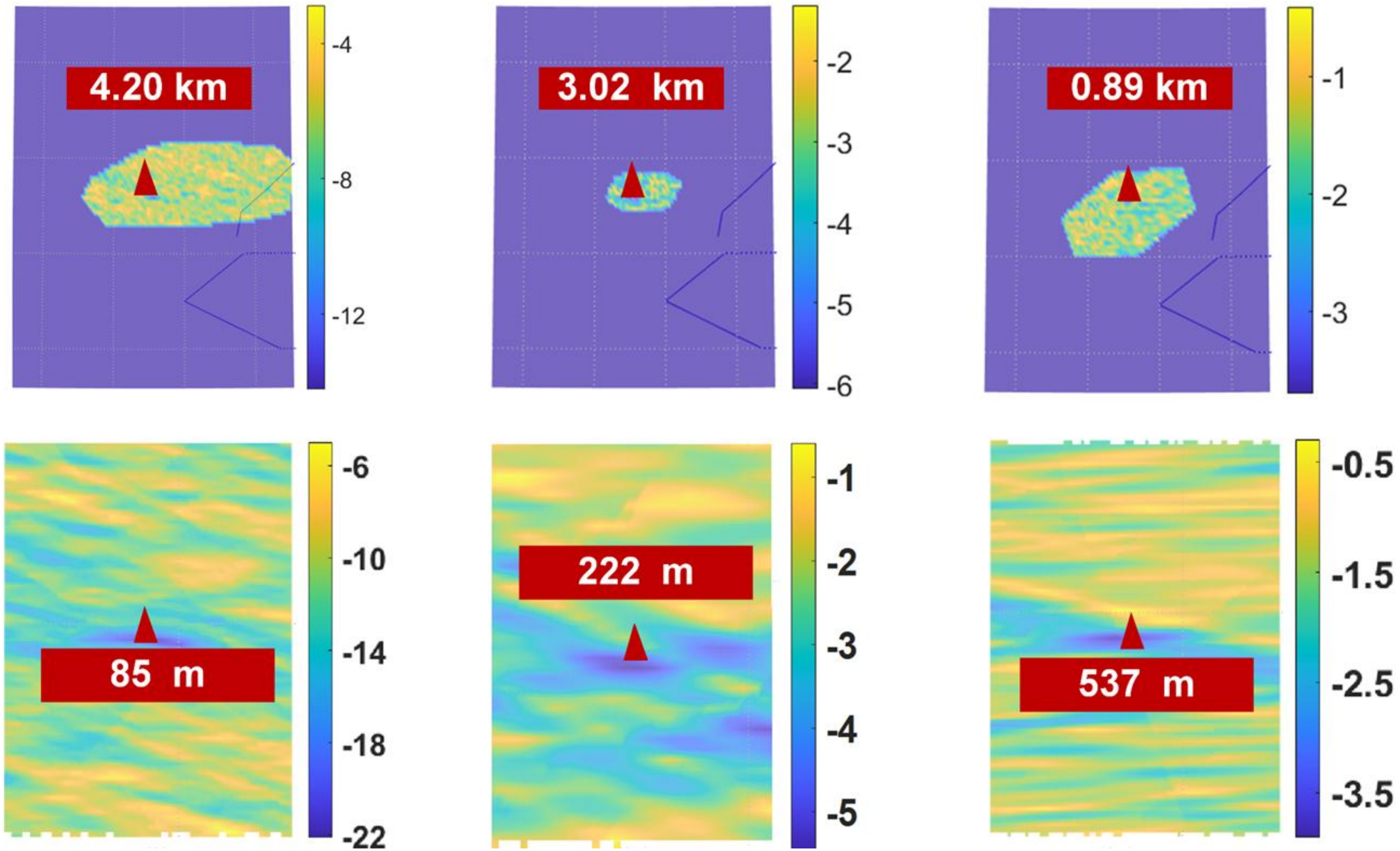
Overhead (85 degrees)

Medium (75 degrees)

Edge (57 degrees)

Coarse-to-Fine localization

- **Results**
  - Example outputs for three elevation angles
  - ~2 km grid space for coarse localization
  - ~200 m grid space for fine localization
  - Non-smooth and sharp cost function can be observed



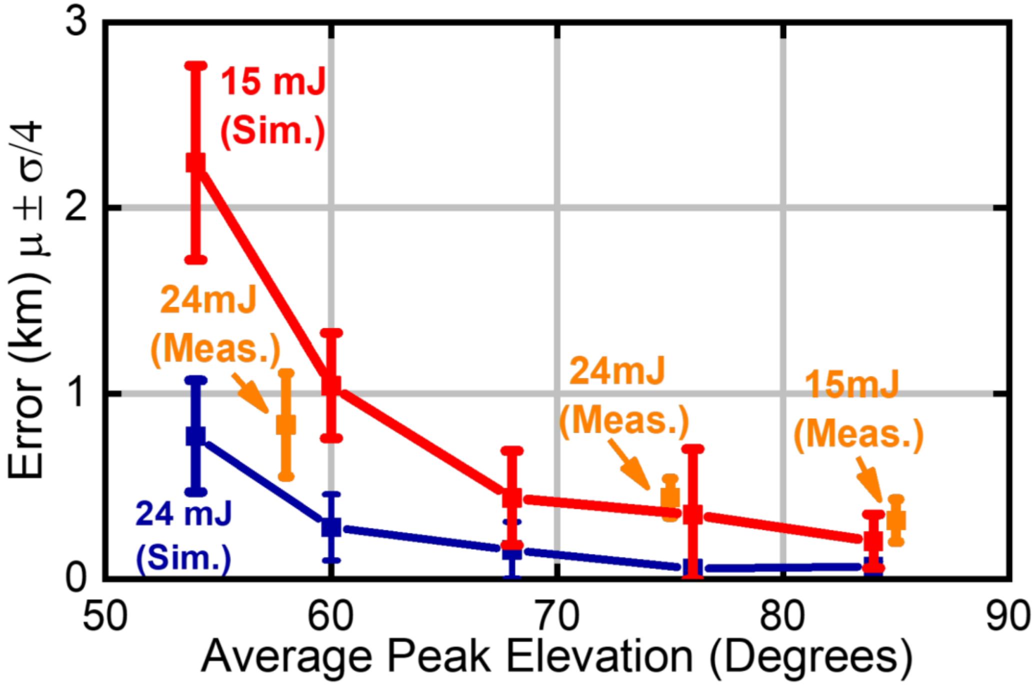
Overhead (85 degrees)

Medium (75 degrees)

Edge (57 degrees)

Statistics of localization accuracy experiments

- **Localization error v.s. average peak elevation**
  - Summary of real-word experiments
    - Three flyovers at low, medium, and high elevation angles
    - ~10 trials of localization at each elevation
    - Mean localization error (320m - 840 m) and standard deviation (230 m - 558 m)
  - Simulation and measurement show consistence



Comparison

- **Comparison among LEO satellites localization**
  - State-of-art **real-word localization performance** with 15-dB lower EIRP and 3x lower energy

	C. Danie et al	M. Murrian et al	Z. Clements et al	P. Ellis et al	Proposed technique
Size constraint	N/A	N/A	N/A	N/A	cm-size
Signal type (Bandwidth)	GMSK 3.84 kHz	GNSS jammer	GNSS jammer	BPSK 2.4 kHz	BPSK 50 kHz
TX EIRP	37.97 dBm	49 dBm	N/A [a]	N/A	23 dBm
Packet energy	62.5 mJ [b]	790 mJ	N/A	N/A	24 mJ
RX power	-112.9 dBm	-107 dBm	N/A	-125 dBm	-132 dBm
Packet length (Interval)	N/A	Continuous	Continuous	Continuous	120 ms (60 s)
Algorithm	TDoA	Doppler time history	Doppler time history	Doppler time history	TDoA , intra-packet Doppler
Accuracy (Sim.)	100-200 m	N/A [c]	N/A	10 m	70-239 m
Accuracy (Meas.)	N/A	N/A	800 m	10 km	320 – 840 m

a. strong GNSS signal jammer/spoofer
b. Assume packet length is 10 ms.
c. Ground truth position unknown

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Summary and future work

- **Summary**
  - Frequency selection and high efficiency customized 1x1 cm antenna
  - Systematic wave optimization for localization accuracy enhancement
  - Low-complexity coarse localization based on TDoA error maps
  - Intra-packet Doppler calibration
  - Three real-word satellites flyover tests
  - Foundation for cm-size tracker implementation in CMOS

- **Future work**
  - CMOS cm-size tracker implementation and test