# Facilitating Novel Modalities for Spectrum Sharing between Earth-Observing Microwave Radiometers and Commercial Users


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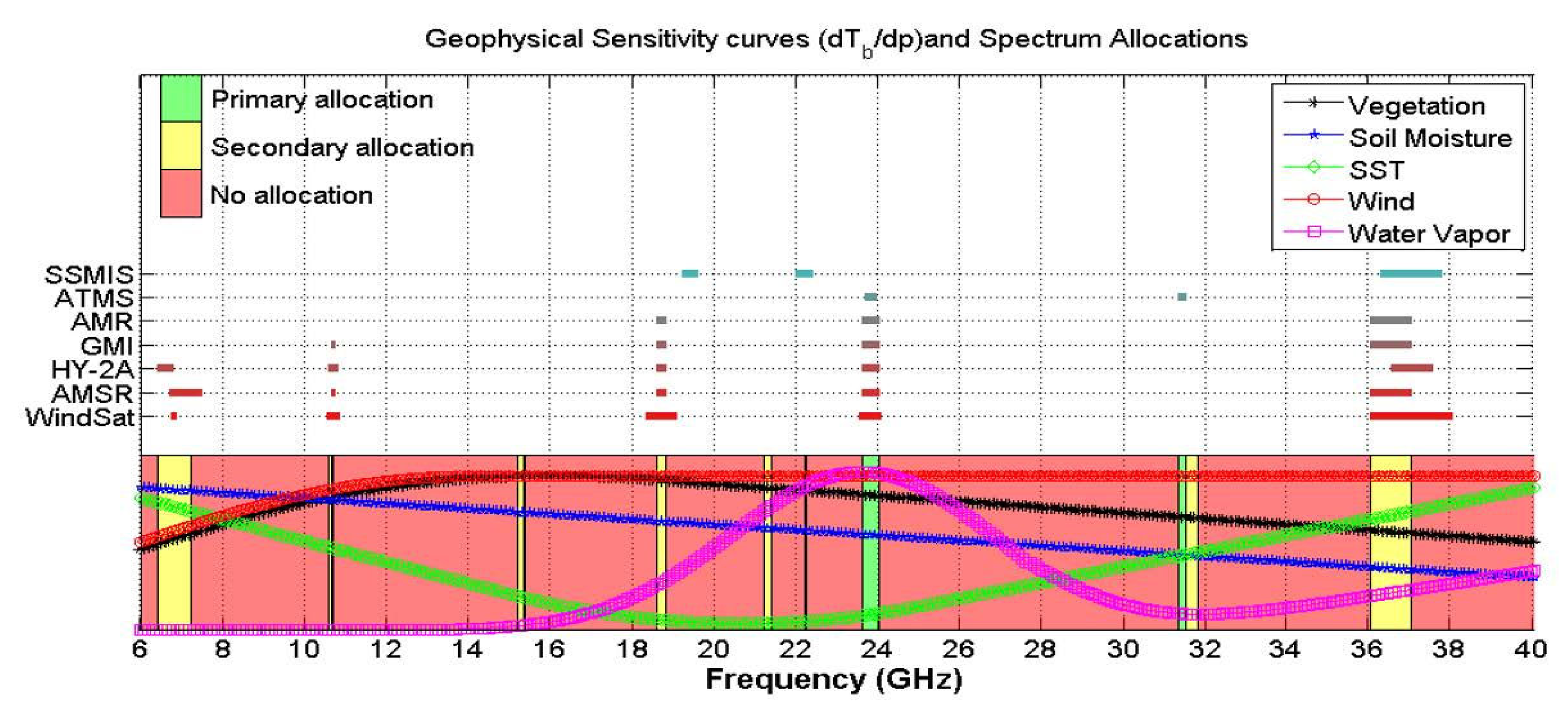
## Project Summary


This project formulates new models for radiometer spectrum access needs that are based on a first principles description of the associated geophysical sensing performance and the unique properties of Earth Exploration Satellite Service (EESS) passive measurements. These models are incorporated into economic frameworks to facilitate the design of a robust commercial market that can co-exist with passive spectrum access by EESS users.


### Radiometer Frequency Allocations and Environmental Property Sensitivity Curves




- Top: Frequency channels (horizontal bars) used by orbiting Earth-observing microwave radiometers from 6-40 GHz.
- Bottom: Spectrum allocations (vertical bars) and sensitivity to Earth environmental properties.

## Intellectual Merit

[1] **J. Chamberlain, J. Johnson, and D. Starobinski, "Spectrum Sharing Between Earth Exploration Satellite and Commercial Services: An Economic Feasibility Analysis," in *2024 IEEE International Symposium on Dynamic Spectrum Access Networks (DySpan)*, 2024**

- Formulated model for open access, pay as you go, commercial service with breakdowns caused by EESS arrivals.
- Determined commercial users are more heavily impacted by system delay than by preemption due to low EESS occupancy rate.
- Provider maximizing pricing coincides with socially optimal behavior - i.e. provider actions do not impose negative externalities on users.
- Leveraged EESS trace data to validate delay model via SimPy, demonstrating breakdowns are consistent with Poisson distributed arrivals.

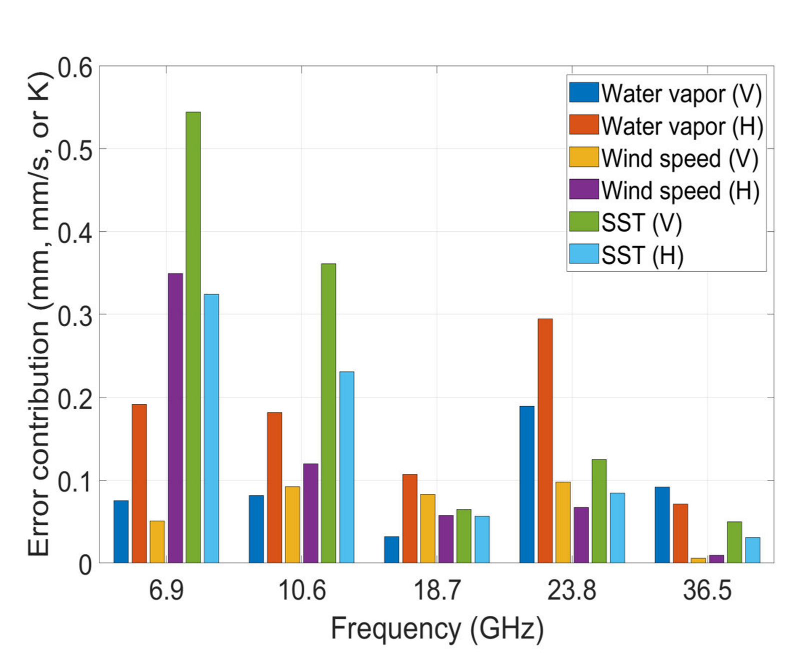
[2] **N. Brendle, J. Johnson, D. Starobinski, and J. Chamberlain, "Estimating the Retrieval Performance of Passive Remote Sensing Under Alternate Spectrum Sharing Scenarios," in *2024 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2024**

- Examined methods for promoting flexible use of spectrum while preserving EESS radiometer access.
- Demonstrated that trade-offs in bandwidth allocations are possible while maintaining acceptable levels of retrieval errors in brightness temperature measurements.

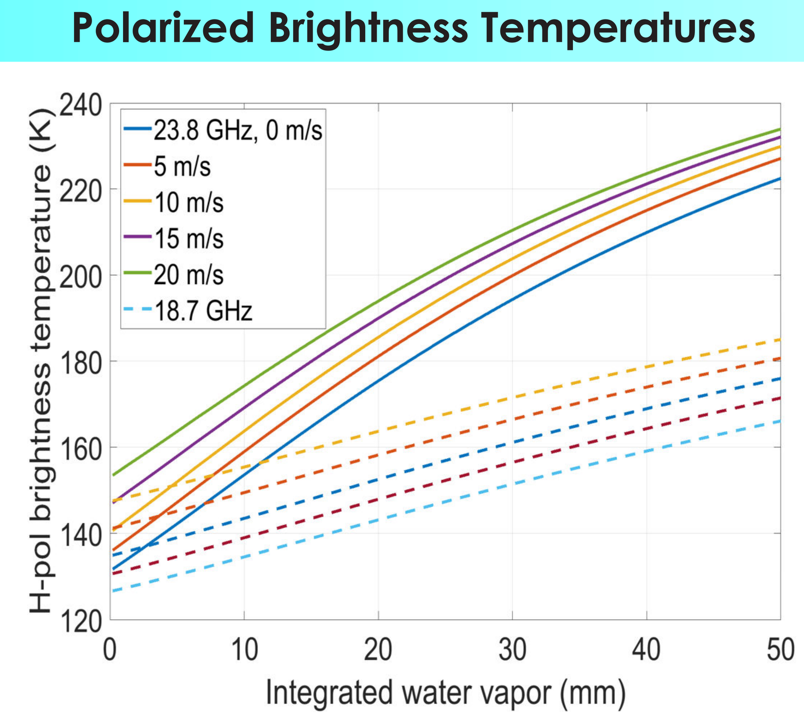
## Broader Impact

1. Promotion of co-existence between scientific and commercial users of high band portion of wireless spectrum.
2. Fostering of new inter-disciplinary research collaborations across remote sensing and wireless networking communities.
3. Traces of satellite radiometer data made available in a convenient format: https://github.com/nislab/passive-radiometer-trace-data

### Brightness Temperature Regression Coefficients

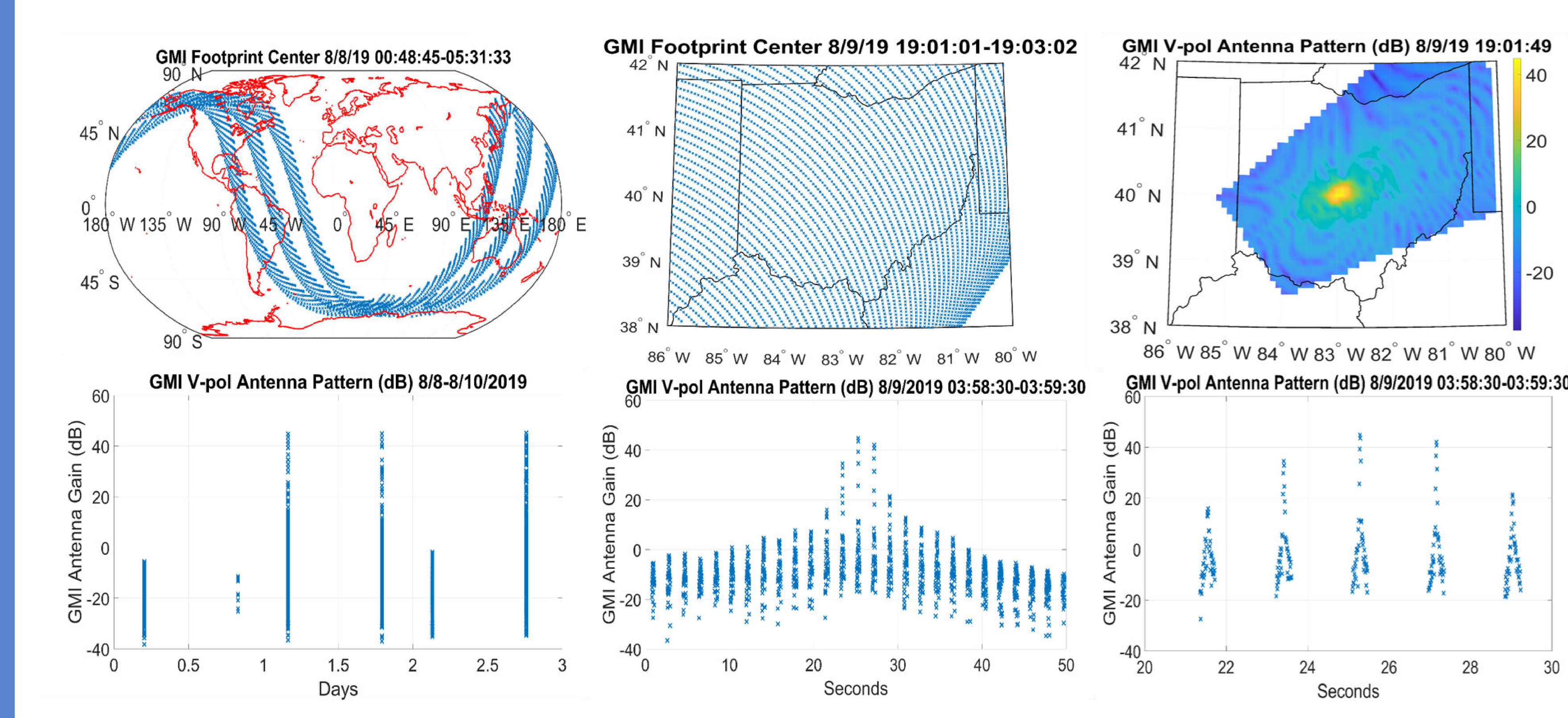



### Predicted Values for Retreived Polarized Brightness Temperatures



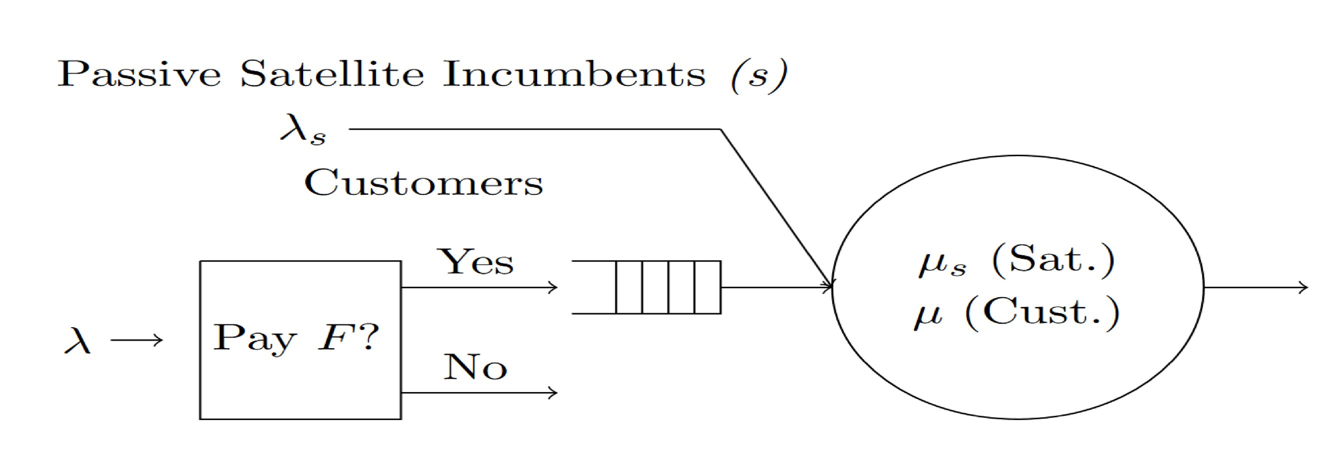

- Left: Regression coefficients for each of 10 brightness temperature measurements to determine retrieval products related to Water Vapor, Wind Speed, and Sea Surface Temperature; the relative contributions of each bar to measurement uncertainties vary depending on the exact allocation of channel bandwidths.
- Right: Predicted horizontally polarized brightness temperatures vs integrated water vapor content and ocean wind speed at 23.8 GHz (solid lines) and 18.7 GHz (dashed lines) for SST 290K and observation angle 55 degrees.

### Analysis of Radiometer Footprints and Arrival Patterns



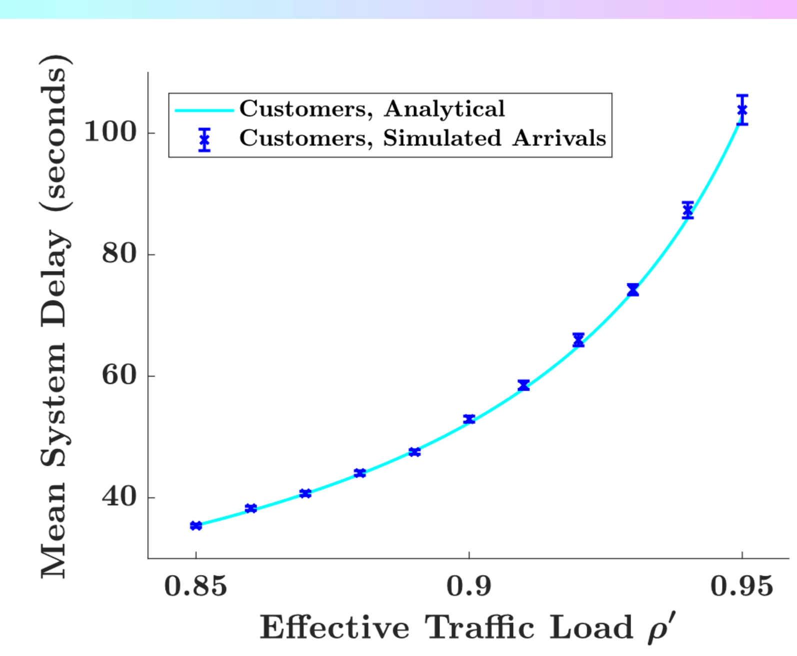

- Top Left: Global footprint locations of the GMI radiometer over an example 5 hour interval period.
- Top Center: Zoom on GMI radiometer footprint locations in a region centered on Columbus, OH over an example 2 hour period.
- Top Right: GMI radiometer vertical polarization antenna pattern (dB), projected onto Earth's surface for a selected footprint measurement from the previous figure.
- Bottom: Time history of GMI vertical polarization gain at Columbus, OH; Bottom Left is the gain over a selected three day period, Bottom Center is a zoom on a 60 second sample of the time history near time 1.75 days of the sample, Bottom Right is a further zoom on a specific 10 second slice within this sample.

### New Joint Queuing-Theoretic and Game-Theoretic Model for Spectrum Sharing

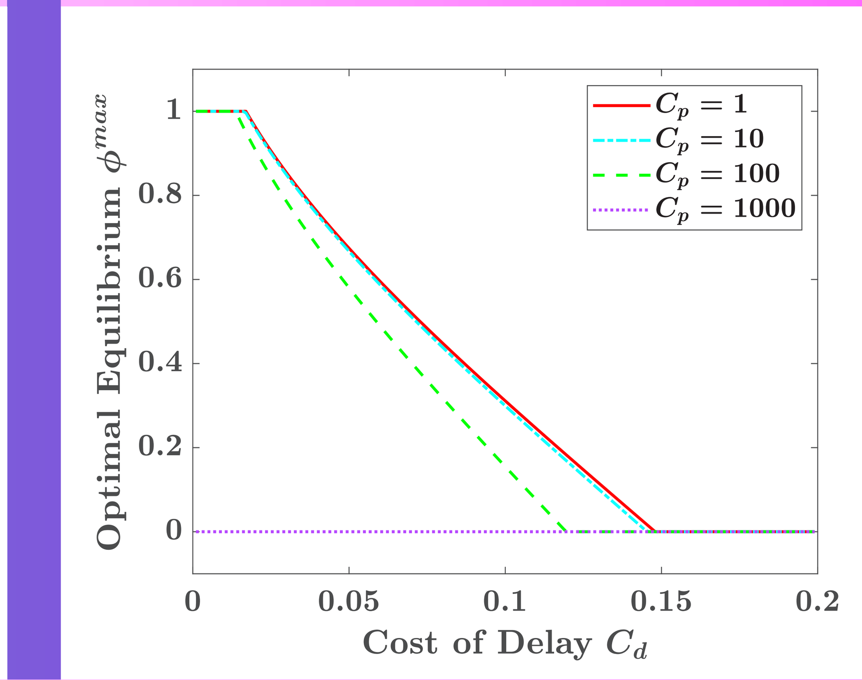



Customers arrive according to a Poisson distributed process and decide whether to join or balk from the queue based on the reward from service, quality of service metrics, and the posted joining fee F, according to an open access spectrum model. Service times follow some general distribution. The queue is subject to breakdowns from the arrival of EESS radiometers, which also follow Poisson arrivals with generally distributed breakdown periods. During a breakdown period, service for customers is suspended, resuming once the radiometer has vacated the area.

### Model Validation with Real Traces




### Evaluating Impact of Delay and Preemptions on Customer Behavior




- Left: Plot of simulated commercial traffic load, incorporating EESS trace data, comparing the mean system delay for the simulated results to the expected delay under heavy traffic loads. We find that the simulated results show good agreement between our model and the data.
- Right: Plot of impact of (relative) Costs of Delay ($C_d$) and Preemption ($C_p$) quality of service metrics on optimal equilibrium under a heavy traffic load scenario. Equilibrium states are defined in terms of the fraction of customers joining the queue. While $C_p$ must be approximately 3 orders of magnitude greater than the reward before all customers elect to balk under any circumstances, this phenomenon occurs when $C_d$ is no greater than 15% of the reward value. This shows that customers are more sensitive to impacts of other customers' actions than EESS preemption.

## Future Directions

1. Statistical analysis of EESS trace data to inform economic models for cooperation between radiometers and commercial users.
2. Development of performance models for radiometers to refine predictions of radiometer usage, ensure non-interference is respected.
3. Creation of portal to facilitate and enhance access to trace data.


## Acknowledgements

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