# Manifold-Based System for Passive-Active Spectrum Sharing

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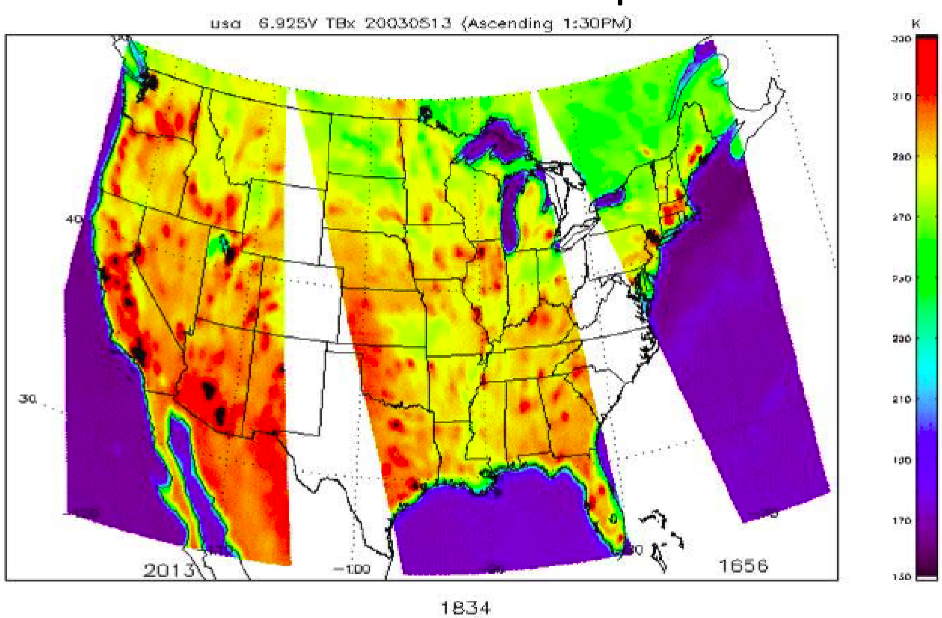
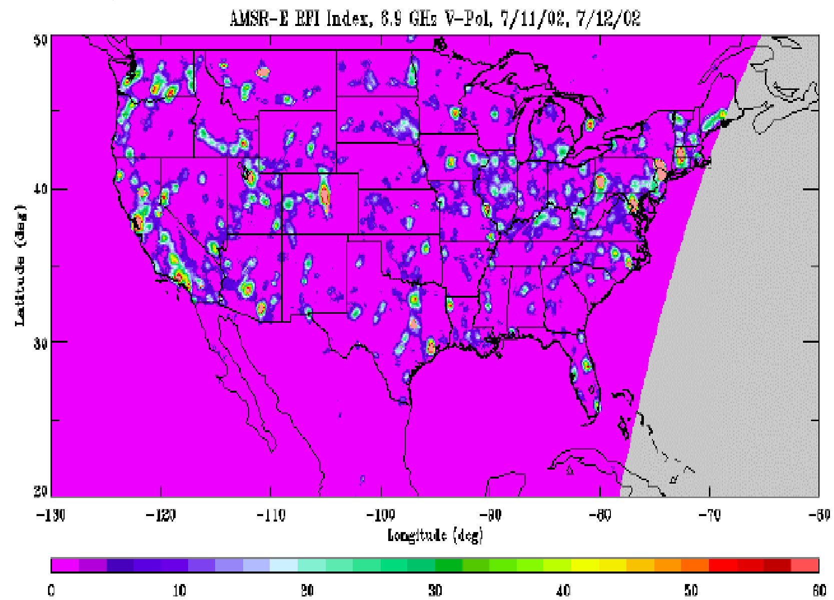
# Problem Statement

**Passive Spectrum Needs:** EESS applications are impacted by RFI at levels as low as 50 mK, but not detectable as RFI below several Kelvins. Required bands are rapidly becoming illuminated by active devices, but the underlying "electrospace" is inefficiently used.

**Efficient Real-Time Allocation of Spectrum:** Develop a decentralized scalable system for near real-time brokering of spectrum requests:

- Based on intersection of electrospace manifolds
- Provides incentive to participate
- Does not consider prioritization
- Focuses on what spectrum **can** be used, not what **should** be used



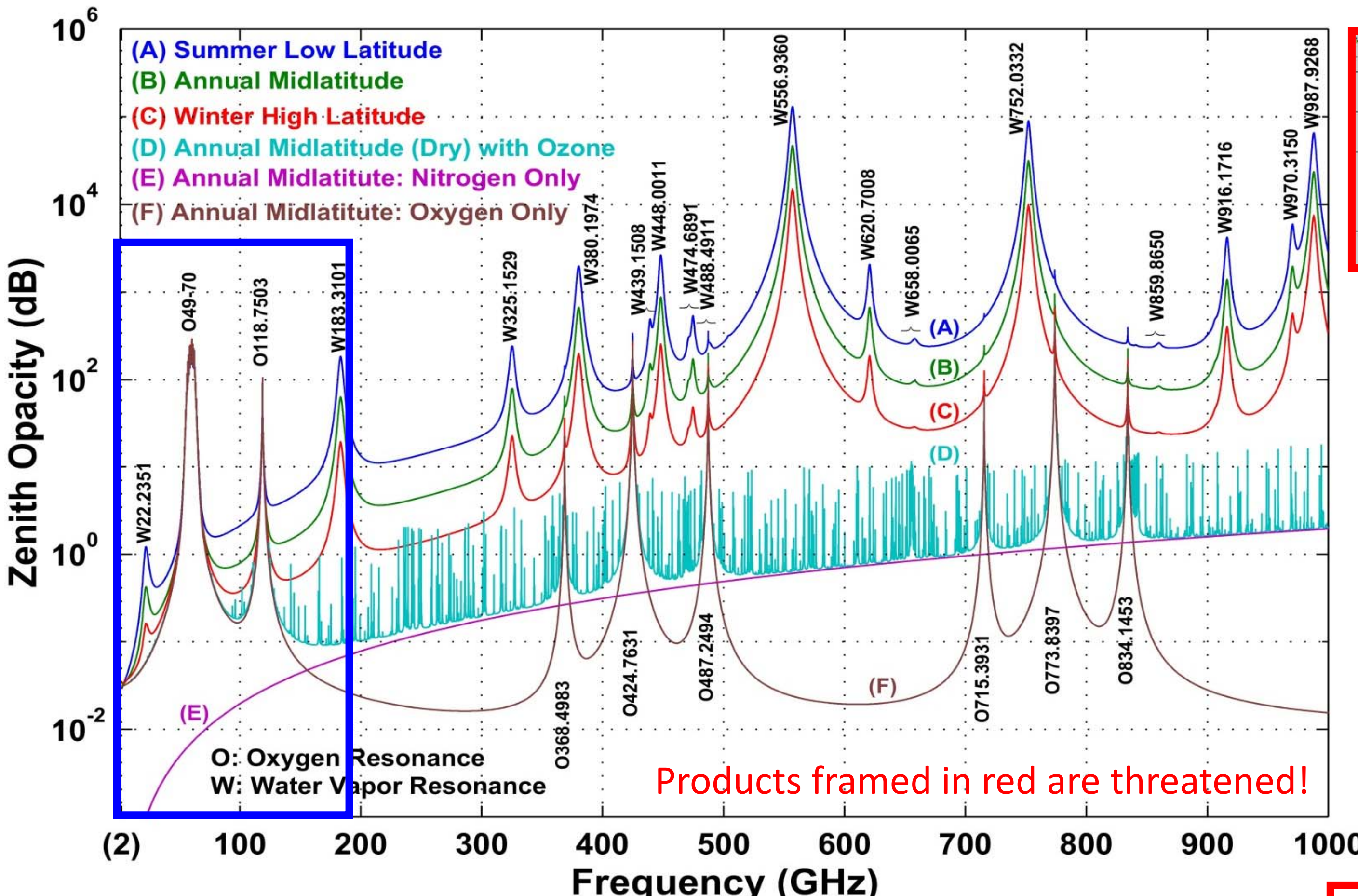



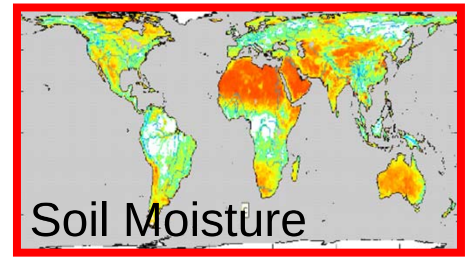
# Merit and Impact

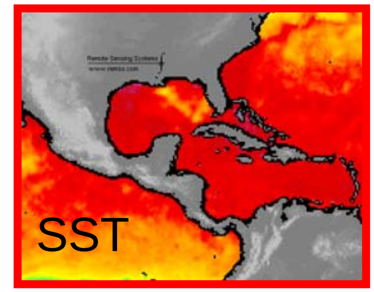
**Intellectual Merit:** This work will contribute a basic knowledge of how active and passive uses of the same spectrum can co-exist, and how emerging technologies, such as frequency agility and the use of network rerouting algorithms to avoid interference can be implemented.

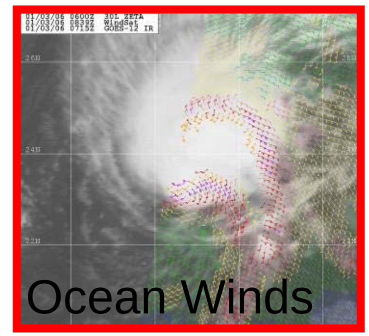
**Broader Impact:** The use of passive spectrum sensing is important for our society, but there is little communication between the radio science community and the networking, technology and regulatory communities on ways to achieve shared use of spectrum while reducing interference. Useful discussions require an evaluation framework, and a central component of this proposal is the development of a demonstration to support such a framework.

# Passive Microwave Environmental Observables

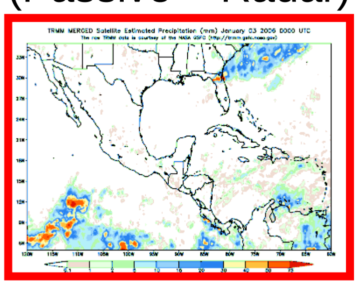


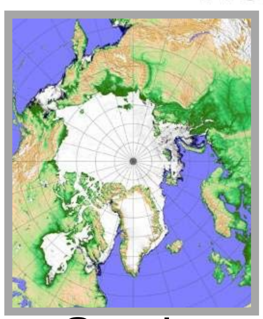


Soil Moisture

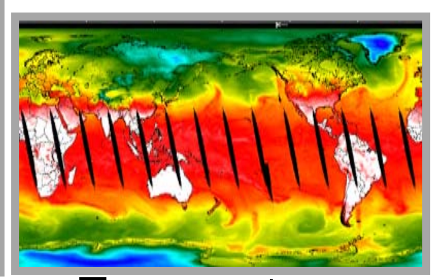

SST

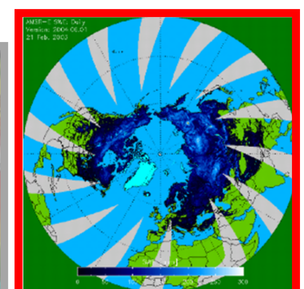

Ocean Winds

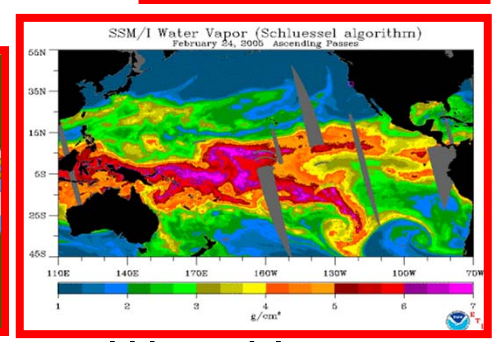
(Passive + Radar)


Precipitation

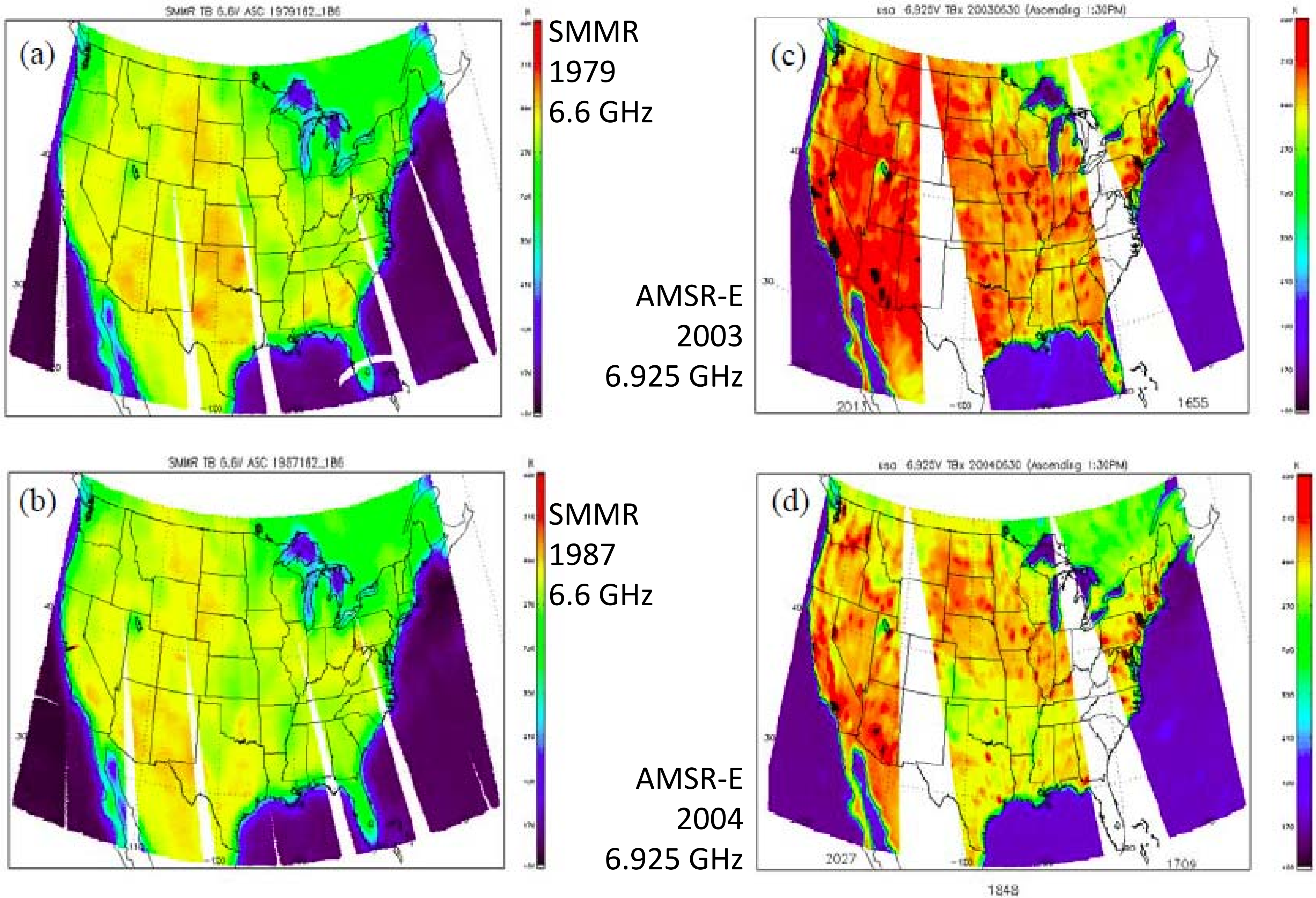

Sea Ice


Temperature


Snow Cover



Water Vapor


(a)
SMMR
1979
6.6 GHz
(b)
SMMR
1987
6.6 GHz
(c)
AMSR-E
2003
6.925 GHz
(d)
AMSR-E
2004
6.925 GHz

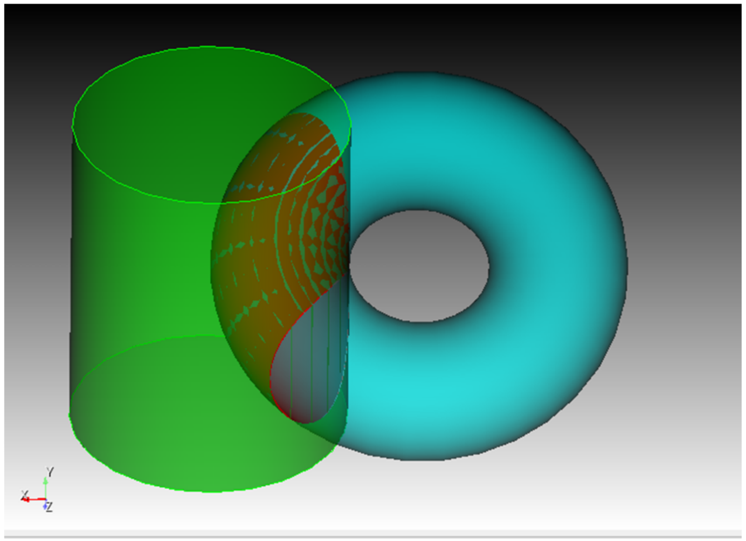
# Manifold-Based System for Passive-Active Spectrum Sharing

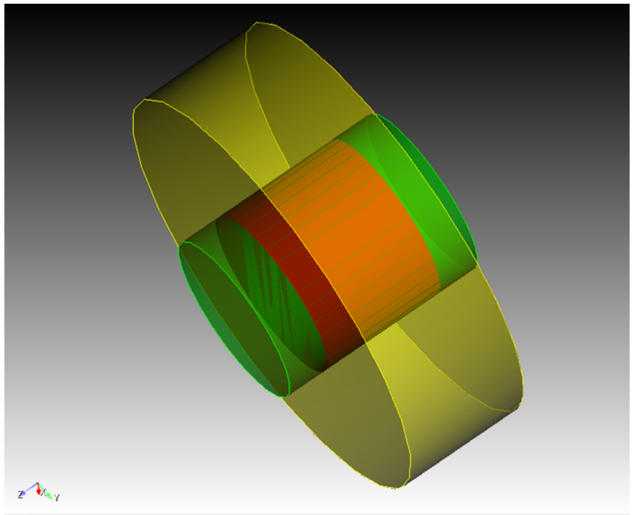
**Objective:** To develop an automated scalable technique for identifying interference in 7-dimensional "electrospace" $(f, x, y, z, \theta, \phi, t)$.

The spectral, spatial, angular, and temporal needs of each eligible service within a band can be defined by a **manifold** (i.e., hypervolume) in 7-D electrospace.

Intersections of manifolds identify **competitive hypervolumes** for which priority-based arbitration or interference flagging can be used.

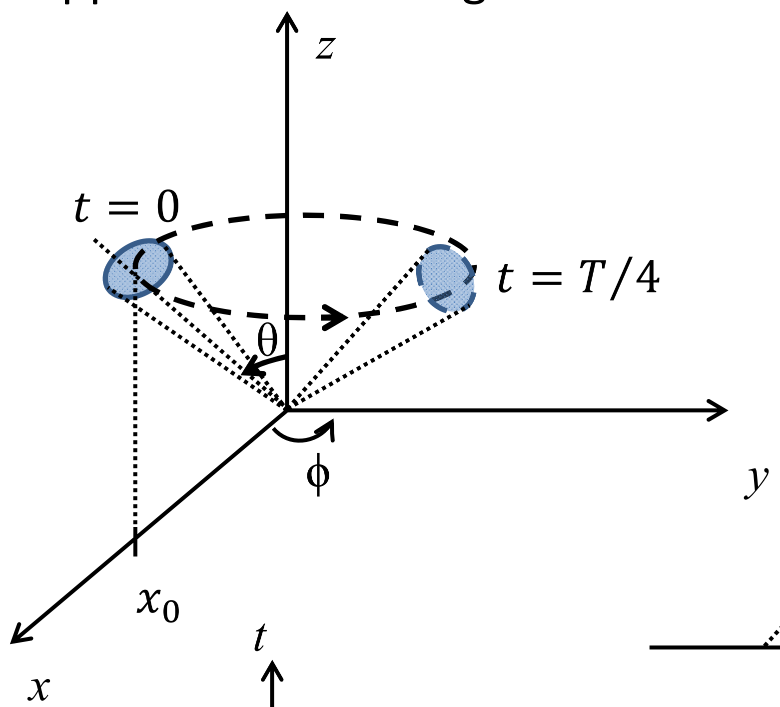
Competitive volumes in 3-D space illustrated by the intersection of one or more 2-D manifolds (i.e., differentiable surfaces)

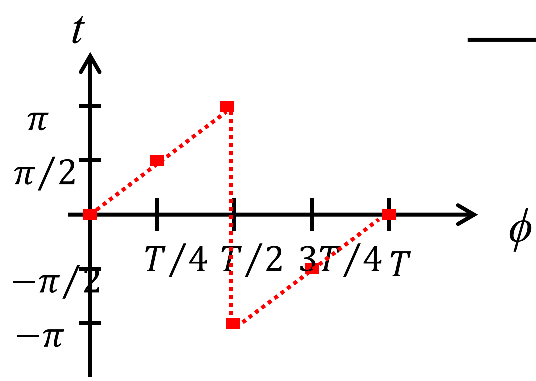


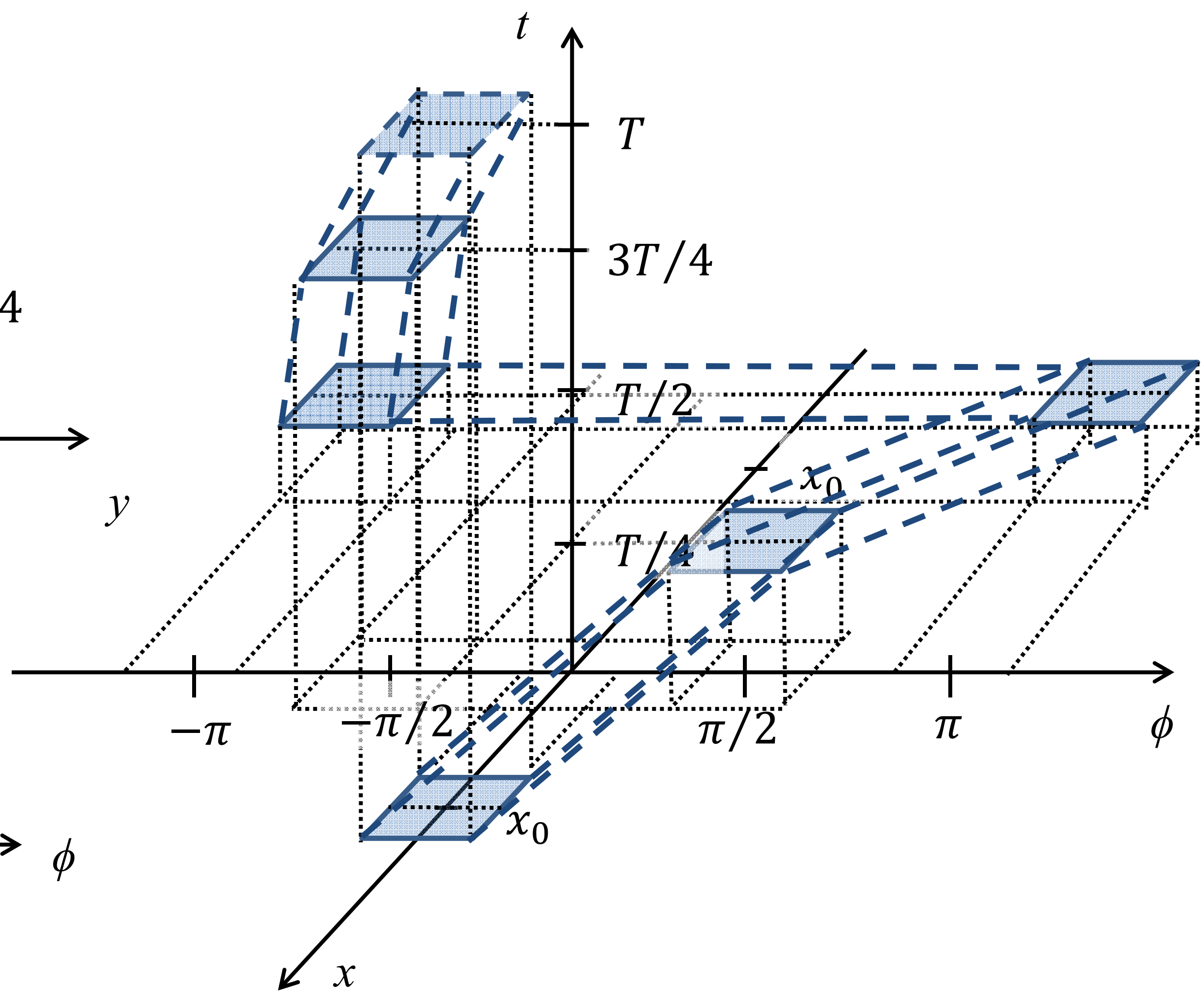


# Visualization of Manifolds
## Ground-Based Terminal Area Radar

Manifolds are most easily visualized by their **3-D slices**. For example, a **conically-scanned terminal area radar** uses a transmit manifold that when sliced in $(x, \phi, t)$ appears as on the right:

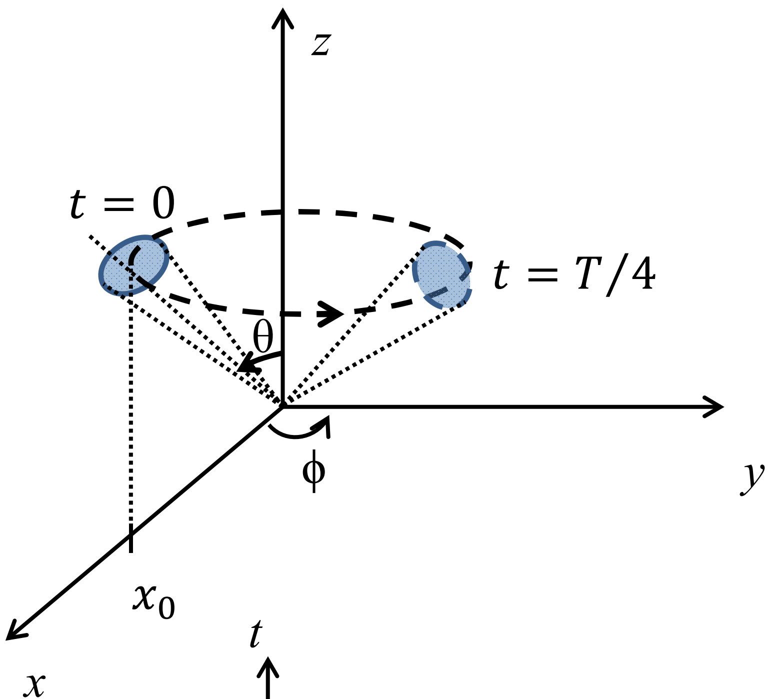


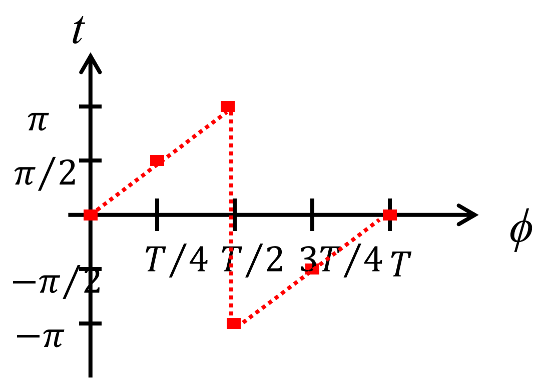



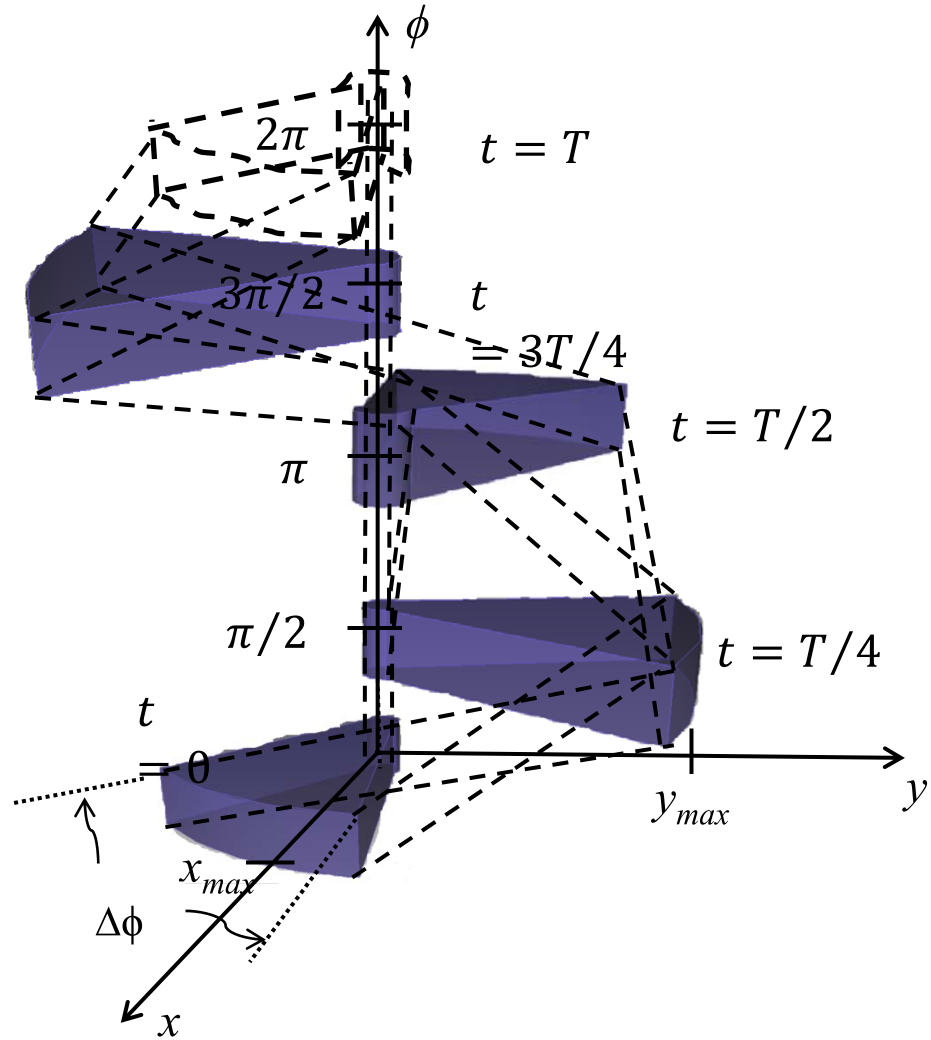



# Visualization of Manifolds
# Ground-Based Terminal Area Radar

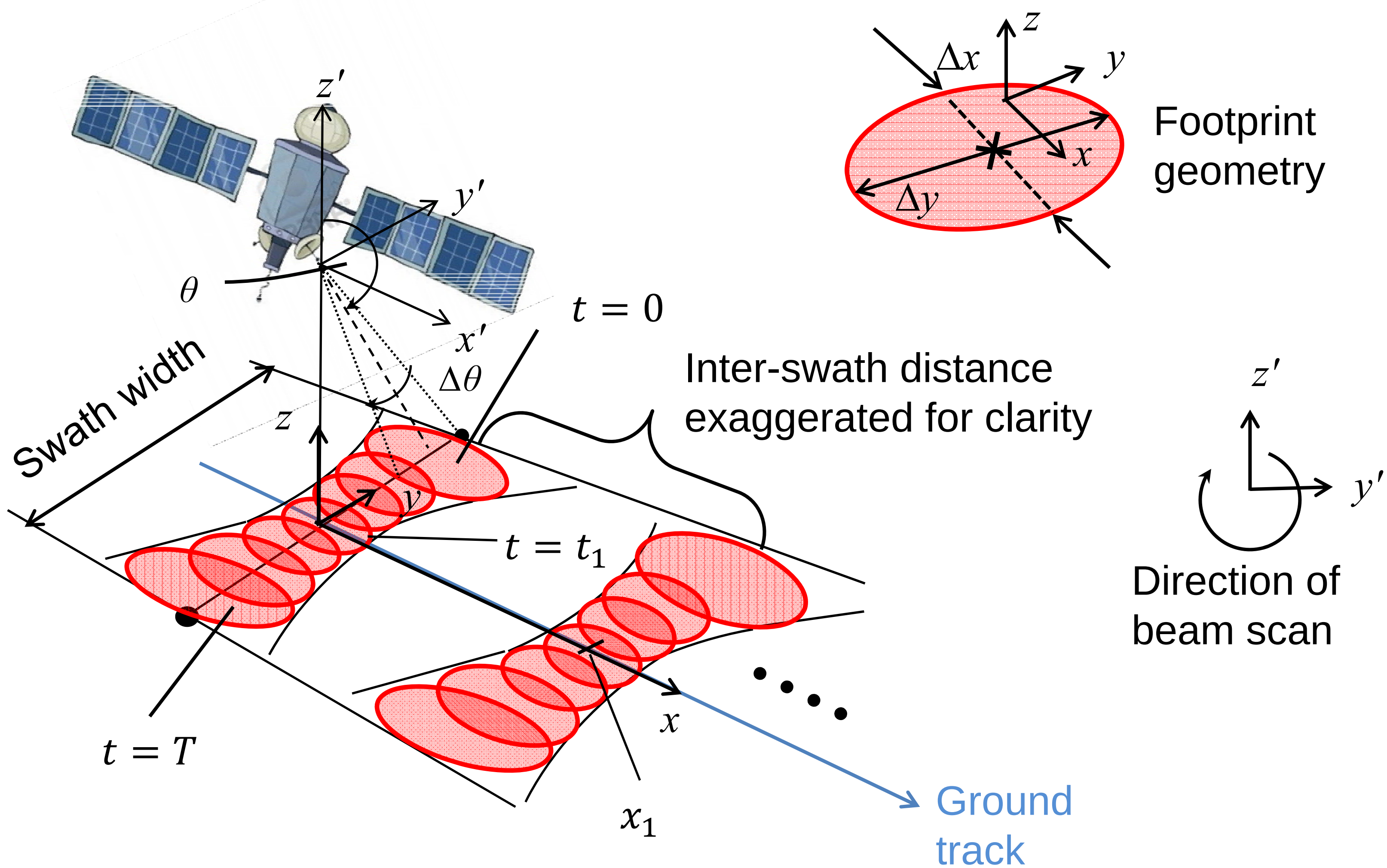
Manifolds can also be depicted as **time-dependent hypervolumes** sliced in 3-D space. The same **conically-scanned terminal area radar** uses a transmit manifold that when sliced in $(x, y, \phi)$ appears as:



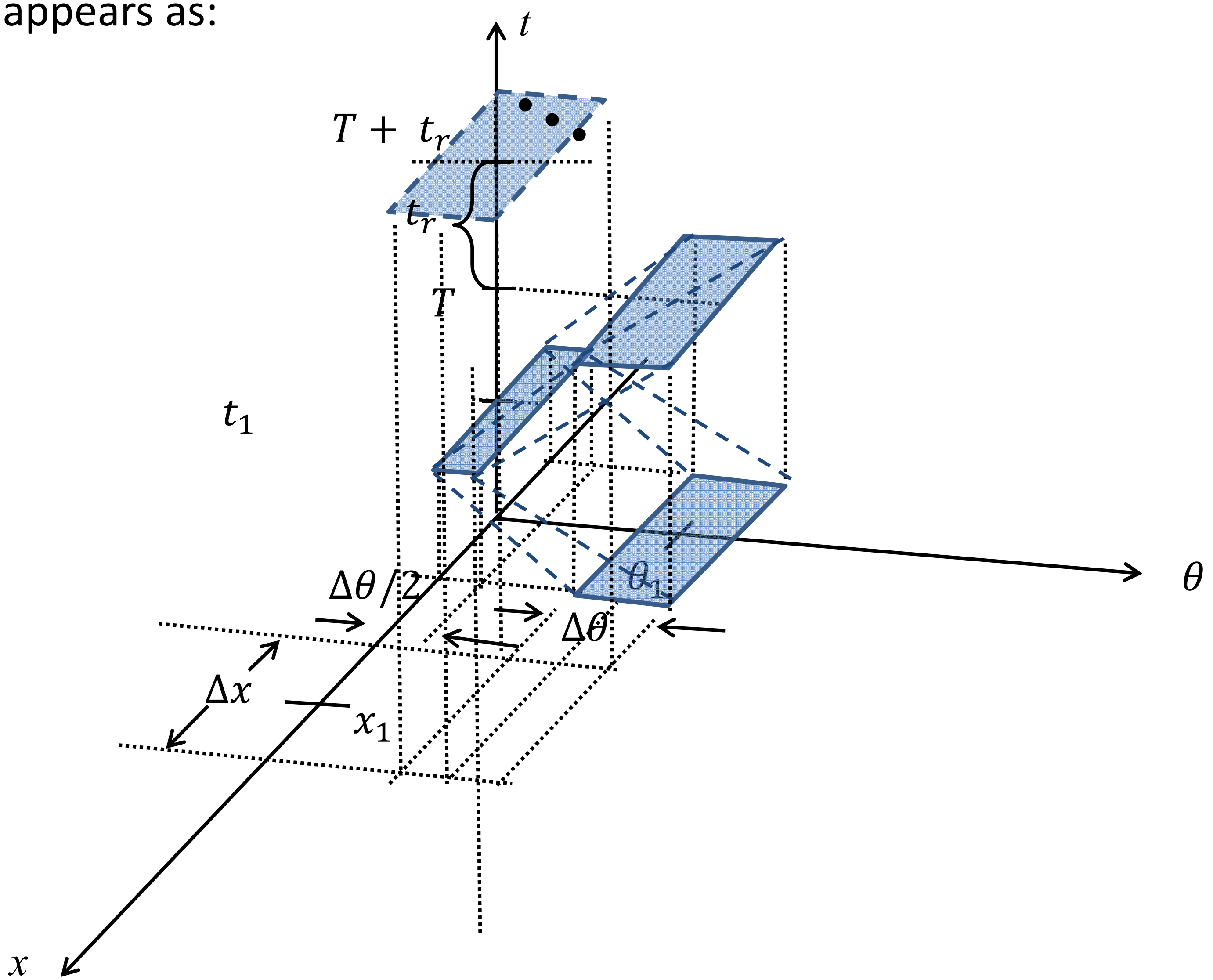



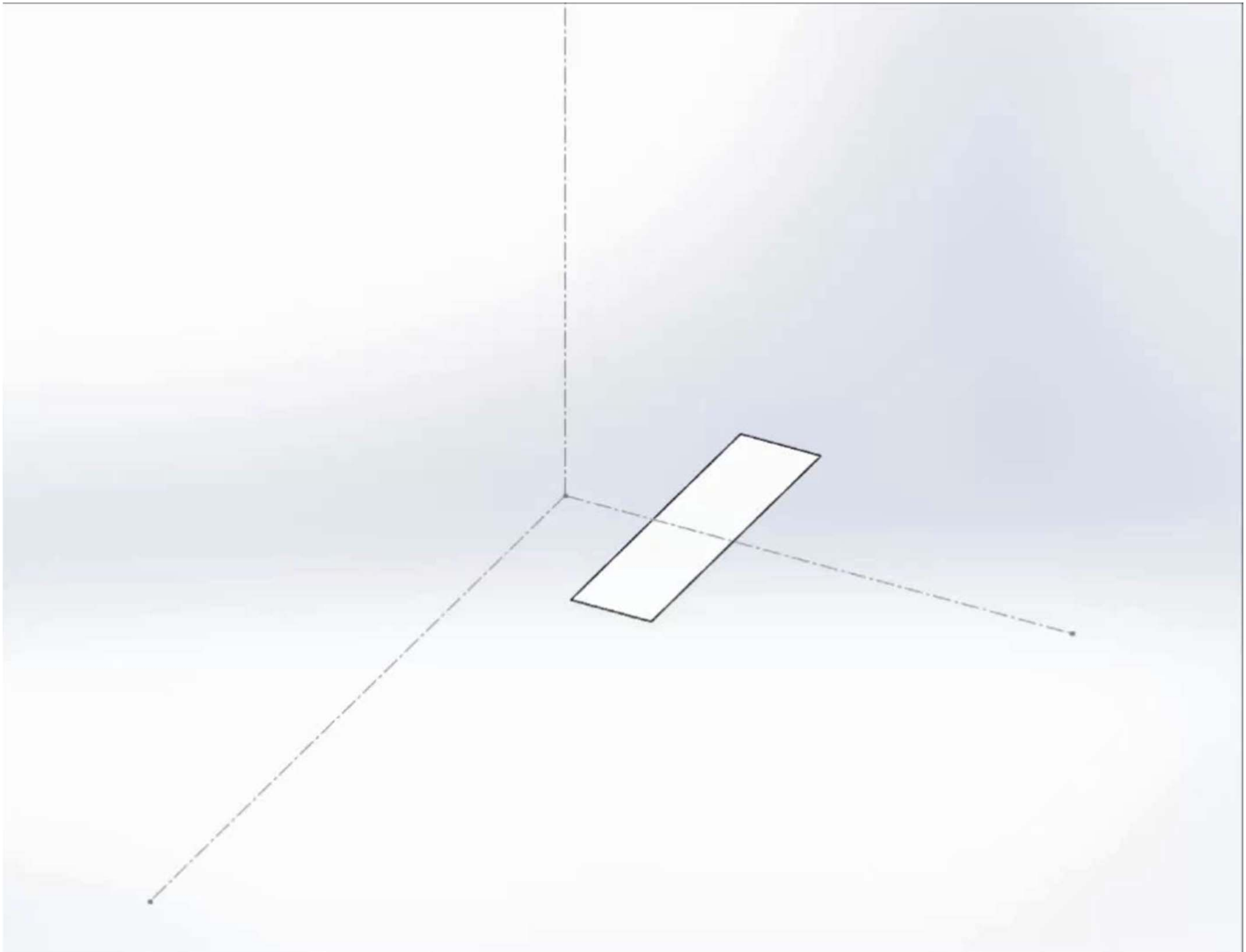
# Visualization of Manifolds
# Spaceborne Cross-Track Sounder



# Visualization of Manifolds
# Spaceborne Cross-Track Sounder

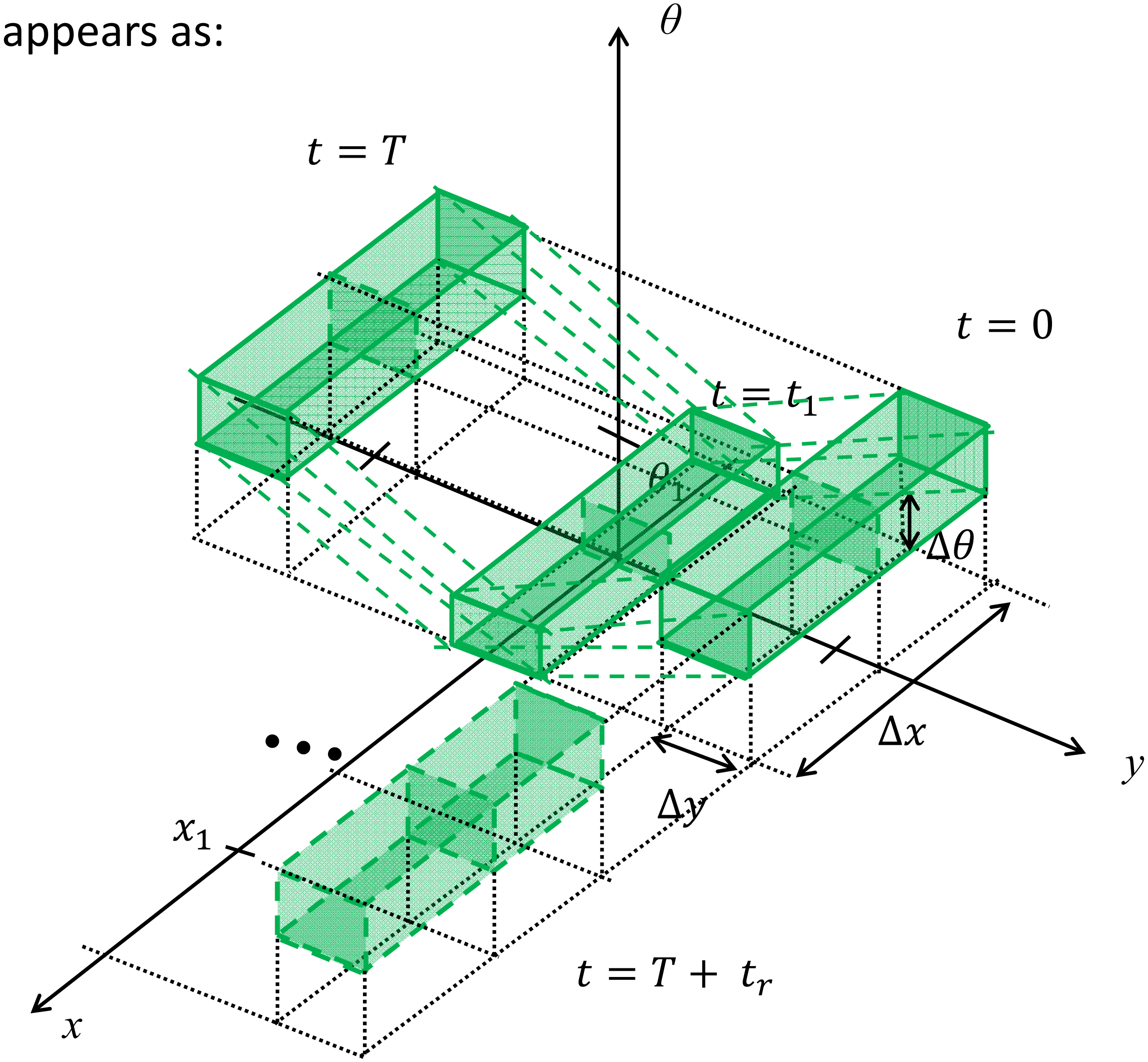
The receive manifold for a **spaceborne cross-track scanned sounder** when sliced in $(x, \theta, t)$ appears as:



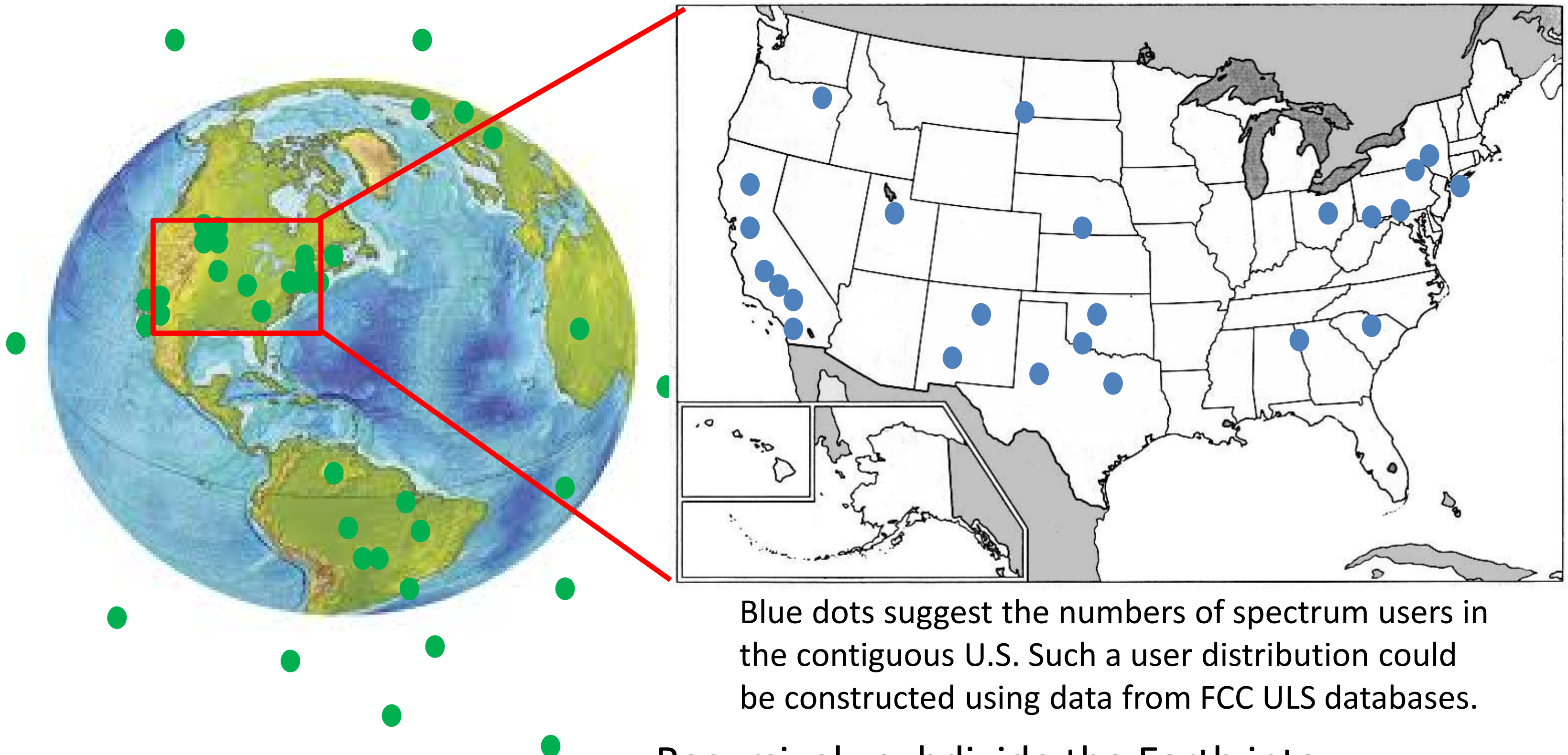


# Visualization of Manifolds
# Spaceborne Cross-Track Sounder

The receive manifold for a **spaceborne cross-track scanned sounder** when sliced in $(x, y, \theta)$ appears as:



# Defining User Domains



Blue dots suggest the numbers of spectrum users in the contiguous U.S. Such a user distribution could be constructed using data from FCC ULS databases.

Green dots suggest the numbers of spectrum users across the globe. Each dot represents a fixed number of users. Dots around the Earth represent satellites or aircraft.

- Recursively subdivide the Earth into geographical user domains.
- (An example of a suitable smallest domain might be the Chicago downtown loop area.)
- Perform manifold intersection study in a distributed fashion after suitable culling of non-intersecting regions.

# Culling

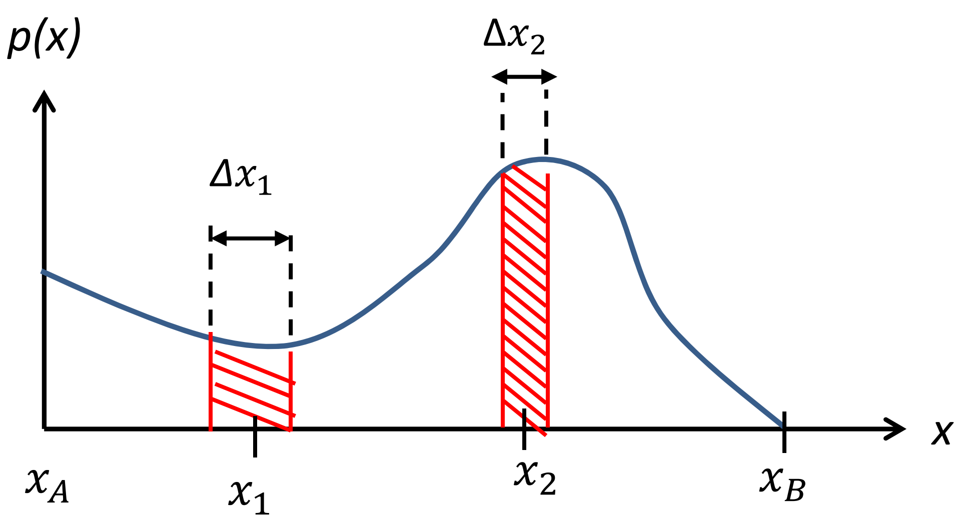
- For *N* users around the globe, number of RFI tests is $N(N-1)/2$
- Each test yields a 2-bit output (xx), global interference vector is of length $N(N-1)$ bits
- Can't perform the above centrally for many reasons
  - Time frame and propagation delay
  - Computer resources
- Within each user domain, **cull** transmit-receive user pairs (i.e. eliminate, transmitter-receiver pairs that are not going to mutually interfere) based on increasingly complex criteria
  - $1^{st}$-order: Subdomain minimum distance
  - $2^{nd}$-order: Cone maintersection
  - $3^{rd}$-order: Friis calculation
- Remaining T/R pairs are flagged for RFI, eligible for interference mitigation based on prioritization, trading schemes, etc…

# First-Order (Distance) Culling

- Criteria #1:
  - Subdomain pairs without LoS are immediately culled
- Criteria #2:
  - Subdomain pairs not close enough to mutually interfere are culled
  - Satellite with large footprints may be a registered as a user in a number of subdomains
- Requires geographical regions of equal computational burden, thus proportional to ratio of computational resources (FLOPS) to expected number of users.

# Equalizing Computational Burden: 1-D

- Let $p(x)$ be the # of users per unit distance
- Total # of users is $N$, domain limits are $x_A$ and $x_B$
- Computing capacity at in each subdomain at location $x_i$ is $c(x_i)$
- Extent of each region is $\Delta x_i$, which is not uniform




User distribution *p(x)* for users along a line $x_B$ - $x_A$

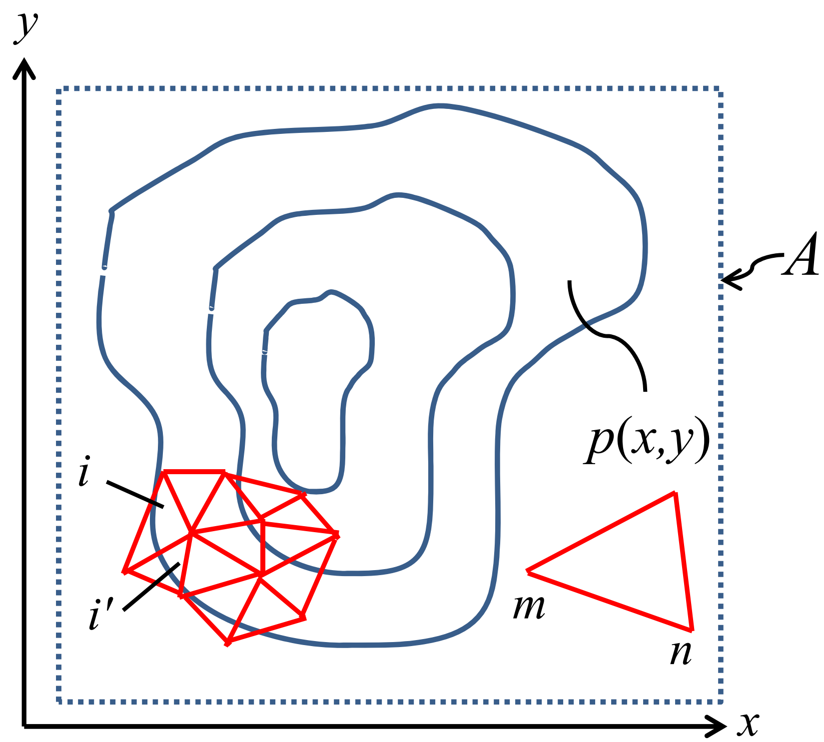
$$\Delta x_i = \frac{\alpha}{p(x_i)} \langle c(x_i) \rangle$$

Constraints:

$$\alpha \sum_i \frac{\langle c(x_i) \rangle}{p(x_i)} = x_B - x_A$$

$$\int p(x)dx = N$$

# First Order Culling: 2-D




Number density of users per unit area $p(x,y)$ can slowly vary with user numbers, as can subdomains

$$p(x_i, y_i)\ A_i \propto \langle c(x_i, y_i) \rangle$$

$$A_i = \frac{\alpha \langle c(x_i, y_i) \rangle}{p(x_i, y_i)}$$

- Subdivide (tesselate) region $A$ into 2-D triangular subdomains
- Area of each subdomain $A_i$ determined subject to constraints
- Total of $P$ subdomains for $N$ users

Constraints:

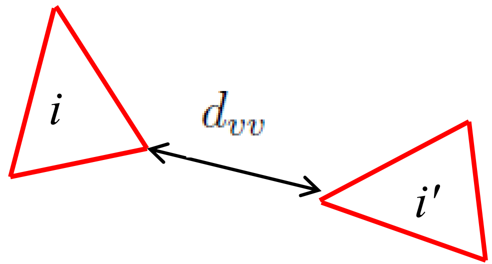
$$\iint_A p(x, y)\ dxdy = N$$

$$\sum_i^P A_i = A$$

$$A_i : \max_{m,n} |\overline{r}_m - \overline{r}_n| \ll \frac{c}{2\Delta t}$$

Where $m$ and $n$ designate the two furthest points in the $i^{th}$ triangle, and $\Delta t \sim 0.001 - 0.250$ sec

# First Order Culling: 2-D




- Determine if users in $i$-th triangle can't interfere with users in $i'$-th triangle
  - If $d_{vv}$ greater than a prescribed distance (see next slide)
- The distance from vertex $(x_i, y_i)$ to $(x_{i'}, y_{i'})$ is:

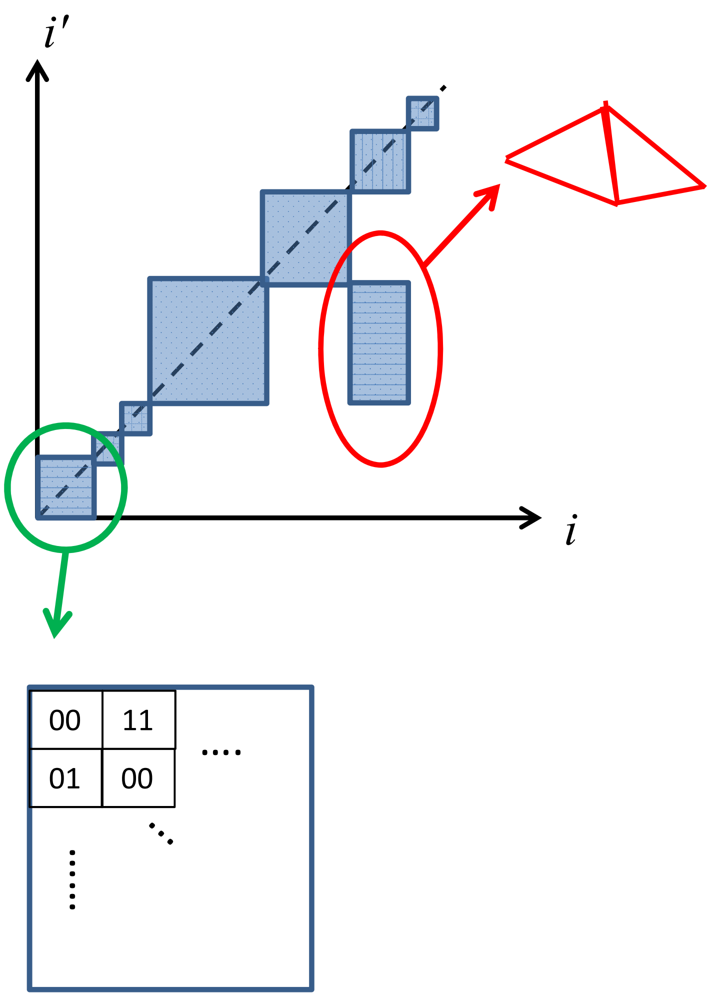
$$\sqrt{(x_i - x_{i'})^2 + (y_i - y_{i'})^2}$$

- Complexity to determine the closest vertex-vertex distance between two triangles, $d_{vv}$ from all 9 possible vertex pairs is:

**9(2A + 2M + 1T) + 8C + 4.5S**

- Update culling mask periodically as subdomains grow/shrink

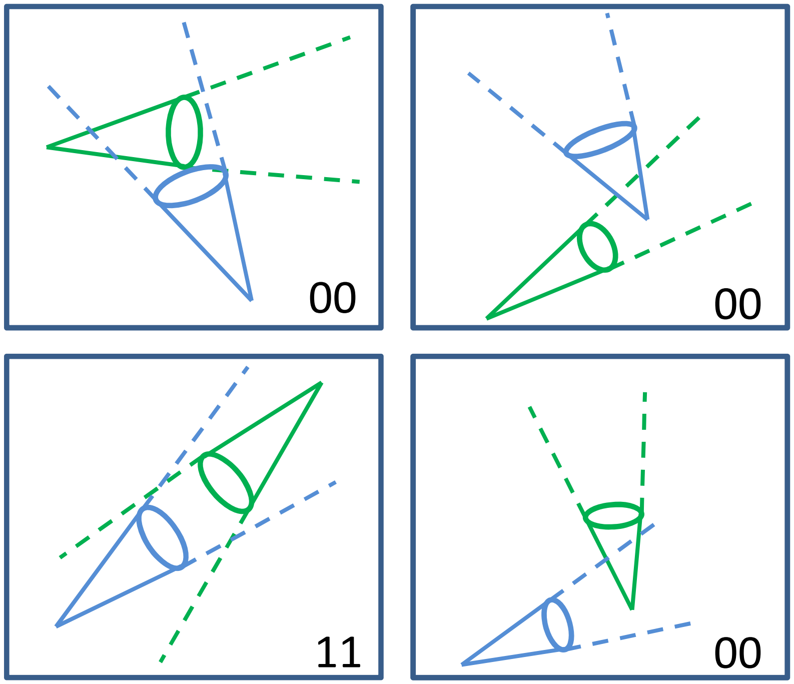
# First Order Culling: 2-D




- First order culling constructs an interference adjacency matrix to proceed with further culling
- Diagonal square user sets represent potential interference between users in the same subdomain
- Off-diagonal user sets represents potential interference across adjacent or nearby subdomains
  - Computational burden assigned to subdomain with larger # of users
- *P* computational centers proceed to solve for interference vector for $E[N/P]$* users each:
  - Interference vector for each subdomain is approximately $\frac{N}{P}\left(\frac{N}{P}-1\right)$ bits long, more or less depending on computational resources
  - Number of flops required per T/R pair is $2^{nd}+3^{rd}$ order complexity times $\frac{\frac{N}{P}(\frac{N}{P}-1)}{2}$

* *$E[N/P]$ is the expected value of (N/P), both $N$ and $P$ are random variables*

# Second-Order (Manifold) Culling




Sample output interference vector for each subdomain considers all pairs $(i,i')$:

00 00 11 11 00 01 11 00 00 00 11 …

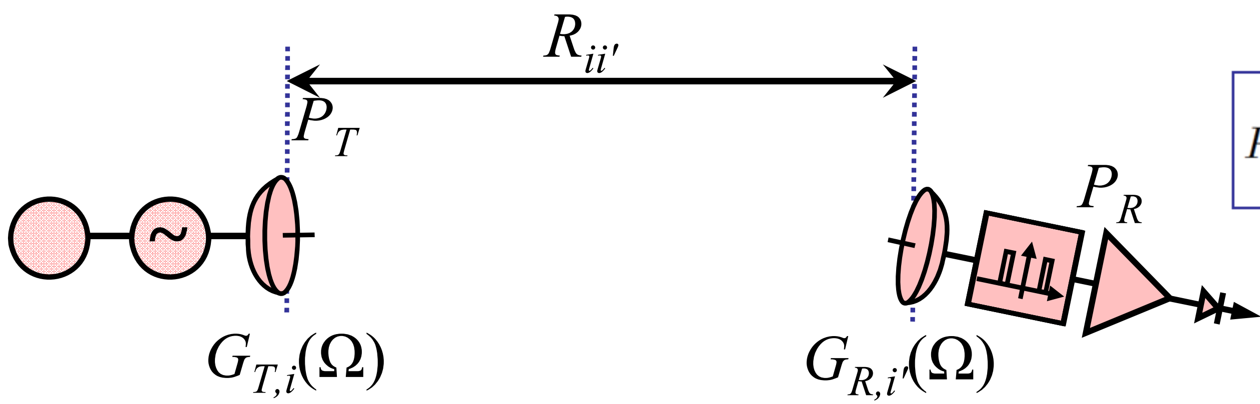
$0 \rightarrow$ no interference to user
$1 \rightarrow$ possible interference to user, proceed to Friis calculation

- For remaining T/R pairs within a subdomain, perform intersection test of their electrospace manifolds in position and angle (Example graphics depict only 2-D space and 1-D angle. actual involves all 5-D)
- Based on idealized and conservative cone approximation to antenna pattern
- Yields a 2-bit output
- T/R pairs with 00 output are culled, others (11) considered for user class and Friis calculation
- User classes determine if interference is possible:
  - e.g. If the green manifold is a passive system, and the blue manifold is an active system, then there is interference to the passive system when the output is 11 (thus set bits to 10)
- Complexity of intersection algorithm for two cones of infinite extent is found to be

**19A + 10M + 5T**

- Number of culled pairs determine # of flops required to produce the interference vector within the required time discretization $\Delta t$

# Third-Order (Friis) Culling




$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2$$

- Final stage of culling yielding RFI flag vector within each subdomain
- Perform Friis calculation between all remaining T/R pairs to determine if EIRP of the $i^{th}$ T/R pair at the receiver of the $i'^{\,th}$ T/R pair exceeds an RFI threshold for user
- Propagation models can be included for more accurate calculations
  - Atmospheric attenuation
  - Building and window penetration
  - Multipath reflection and diffraction (approximate models)
- Complexity is **9A + 19M + 4T**

# Spectrum User Classification

## Spectrum Users

**Fixed**
- WiFi
- Time Doppler Weather Radar
- Radio astronomy

**Mobile**
- Cellular communications
- Police/fire department comms.

**Satellites**
- Passive e.g. WindSat, AMSR-2, SMAP (future mission), SMOS, Aquarius
- Active e.g. CloudSat, CALIPSO

Descriptor language must define manifold spatial and angular extent as dependent on user type, along with transmitted power and band, and RFI receive power threshold and bandwidth.

# Spectrum User Classification

- Current work includes defining a suitable manifold descriptor language for each class of users
  - Antenna gain (parameterized for fast lookup)
  - Position, or position vs time (e.g., Keplerian orbital elements for satellites can provide position velocity information)
  - Attitude, or attitude vs time (e.g.,. scanning task schedule)
  - Transmit power (active systems) and band
  - Receiver RFI sensitivity threshold (all receiver systems) and bandwidth
  - Polarization (useful for multipath calculations)
- Submitted binary descriptor for any user must be a highly compact string of bits.
- "Spectrum Usage Descriptor Language" (SUDL)

# Manifold Based Sharing: Objectives and Challenges

**Planned Engineering Demonstrations:**

- Queries into existing databases (e.g., ULS) using standard query language (SQL) to develop experimental user data base
- WindSat and C-band wifi network experiment: Demonstrate seamless delay-intolerant rerouting of network traffic during overpass of WindSat footprint.
- Interlaced ground-based radiometer scanned observations and C-band WiFi network experiment

**Fundamental Challenges:**

- Demonstration of *N*-scalable rapid manifold algorithm and optimization of algorithm complexity: System must be able to handle large number of user service requests.
- Potential applications on distributed GPUs using constructive solid geometry algorithms
- Consideration of optimum $\Delta t$ given backhaul latency, propagation, and computation delays

# Summary

**The CU EARS project focuses on:**

- Developing and demonstrating a **scalable distributed manifold-based method** for identifying RFI and allocating spectrum requests in real time

- The **goal** is to improve use of electrospace and expand bands for which passive environmental measurements can be made

- Applicability is aimed at arbitrary active and passive users of the spectrum, and provides incentives to participate.

- A project goal is the limited demonstration of a system using a C-band spaceborne radiometer and local WiFi network.

# References


[1] J. W. Allen, T. X Brown, D. C. Sicker, and J. Ratzloff. Proc. of the International Symposium on Advanced Radio Technologies. NTIA Special Publication SP-04-409, Springfield, VA, 2004.

[2] E. Anderson, C. Phillips, D. Sicker, and D. Grunwald. Signal quality pricing: Decomposition for spectrum scheduling and system configuration. In New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on, pages 408 –419, may 2011.

[3] Eric Anderson, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. Modeling environmental effects on directionality in wireless networks. Mathematical and Computer Modeling, 2010. To Appear.

[4] Eric Anderson, Gary Yee, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. The impact of directional antenna models on simulation accuracy. In 7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2009.

[5] H. S. Berger, K. R. Kontson, A. E. Leu, T. X Brown, F. Frantz, D. M. Parker, V. Prasad, and D. Stewart. IEEE recommended practice for the analysis of in-band and adjacent band interference and coexistence between radio systems. IEEE Standard P1900.2-2008, 29 July 2008.

[6] J. B. Bernthal, T. X Brown, D. N. Hatfield, D. C. Sicker, P. A. Tenhula, and P. J. Weiser. Trends and precedents favoring regulatory embrace of smart radio technologies. In IEEE Dynamic Spectrum Access Networks (DySpAN), Dublin, April 17–20 2007.

# References

[7] T. X Brown. Enabling and evaluating unlicensed operation in the TV broadcast bands. Technical Report Docket No. 04-186, reply comments In the matter of Unlicensed Operation in the TV Broadcast Bands, Federal Communications Commission, Jan. 29 2005.

[8] T. X Brown. A harmful interference model for unlicensed device operation in licensed service bands. J. of Communications, 1(1):13–25, April 2006.

[9] T. X. Brown, Sheetalkumar Doshi, Sushant Jadhav, Daniel Henkel, and Roshan-George Thekkekunnel. A full scale wireless ad hoc network test bed. In Proceedings of ISART'05, NTIA Special Publications SP-05-418, pages 51–60, March 2005.

[10] T. X Brown, J. E. James, and A. Sethi. Jamming and sensing of encrypted wireless ad hoc networks. In Proc. Seventh ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), Florence, May 22-25 2006.

[11] T. X Brown and A. Sethi. Potential cognitive radio denial-of-service vulnerabilities and protection countermeasures: A multi-dimensional analysis/assessment. In Proc. Second Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), Orlando, FL, Aug 1–3 2007.

[12] T. X Brown and A. Sethi. Potential cognitive radio denial-of-service vulnerabilities and protection countermeasures: a multi-dimensional analysis and assessment. Journal of Mobile Networks and Applications, July 2008.

# References

[13] T. X Brown and D. Sicker. Can cognitive radio support broadband wireless access? In IEEE Dynamic Spectrum Access Networks (DySpAN), Dublin, April 17–20 2007.

[14] T. X Brown and D. C. Sicker. Examining the viability of broadband wireless access under alternative licensing models in the TV broadcast bands. EURASIP Journal on Wireless Communications and Networking, 2008, January 2008.

[15] L. Chen, S. H. Low, M. Chiang, and J. C. Doyle. Cross-layer congestion control, routing and scheduling design in ad hoc wireless networks. In IEEE Infocom, April 2006.

[16] Marshall H. Cohen, Albin J. Gasiewski, Donald C. Backer, ROberta Balstad, Steven W. Ellingson, Darrel Emerson, Aaron S. Evans andJoel T. Johnson, Paul Kolodzy, David B. Kunkee, Molly K. Macauley, James M. Moran, Lee G. Mundy, Timothy J. Pearson, Christopher S. Ruf, Frederick S. Solheim, David H. Staelin, and Alan B. Tanner. Spectrum Management for Science in the 21st Century. National Academies Press, Washington, D.C., 2010.

[17] CRAWDAD: A Community Resource for Archiving Wireless Data At Dartmouth, 2008. http://crawdad.cs.dartmouth.edu/.

[18] R. Dhillon and T. X Brown. Models for analyzing cognitive radio interference to wireless microphones in TV bands. In IEEE Dynamic Spectrum Access Networks (DySpAN), Chicago, Oct. 14–17 2008.

# References

[19] Christain Doerr, Troy Weingart, Douglas Sicker, and Dirk Grunwald. Multimac an adaptive mac framework for dynamic radio networking. In DySPAN (Dynamic Spectrum Access Networks), 2005.

[20] Aveek Dutta, Dola Saha, Dirk Grunwald, and Douglas Sicker. Smack: a smart acknowledgment scheme for broadcast messages in wireless networks. In SIGCOMM '09: Proceedings of the ACM SIGCOMM 2009 conference on Data communication, pages 15–26, New York, NY, USA, 2009. ACM.

[21] Aveek Dutta, Dola Saha, Dirk Grunwald, and Douglas Sicker. An architecture for software defined cognitive radio. In ANCS '10: Proceedings of the 4th ACM/IEEE Symposium on Architectures for Networking and Communications Systems, New York, NY, USA, 2010. ACM.

[22] Aveek Dutta, Dola Saha, Dirk Grunwald, and Douglas Sicker. Practial implementation of blind sychronization in NC-OFDM based cognitive radio networks. In Proceedings of the Workshop on Cognitive Radio Networks (CoRoNet'10), Sept 2010.

[23] Aveek Dutta, Dola Saha, Dirk Grunwald, and Douglas Sicker. Practical implementation of blind synchronization in NC-OFDM based cognitive radio networks. In CoRoNet '10: Proceedings of the 2009 ACM workshop on Cognitive radio networks, New York, NY, USA, 2010. ACM.

[24] KAREN ST. GERMAIN, MICHAEL DAVIS, DAVID DeBOER, STEVEN W. ELLINGSON, AARON S. EVANS, JAMES M. MORAN, JEFFREY PIEPMEIER, MELINDA PIKET-MAY, F. PETER SCHLOERB, DANIEL SMYTHE, PAUL A. VANDEN BOUT, and LUCY ZIURYS. Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses. National Academies Press, Washington, D.C., 2007.

# References


[25] K. Harrison, S.M. Mishra, and A. Sahai. How much white-space capacity is there? In New Frontiers in Dynamic Spectrum, 2010 IEEE Symposium on, pages 1 –10, apr. 2010.

[26] Daniel Henkel, Cory Dixon, Jack Elston, and Timothy X Brown. UAV sensor data collection test bed. In submitted to Proc. of RealMAN, 2006.

[27] Abdul Jabbar, Bharatwajan Raman, Victor S. Frost, and James P. G. Sterbenz. Weather disruptiontolerant self-optimising millimeter mesh networks. In Proceedings of IWSOS : Third International IFIP/IEEEWorkshop on Self-Organizing Systems, volume 5343 of Lecture Notes in Computer Science, pages 242–255. Springer, 2008.

[28] Abdul Jabbar, Justin P. Rohrer, Andrew Oberthaler, Egemen K. C¸ etinkaya, Victor S. Frost, and James P.G. Sterbenz. Performance comparison of weather disruption-tolerant cross-layer routing algorithms. In INFOCOM 2009. The 28th Conference on Computer Communications. IEEE, pages 1143–1151, April 2009.

[29] S. Jadhav, T. X Brown, S. Doshi, D. Henkel, and R.-G. Thekkekunnel. Lessons learned constructing a wireless ad hoc network test bed. In Proc. of the Wireless Network Measurement Workshop, Trentino, Italy, April 2005.

[30] A. Knoll, I. Wald, S. Parker, and C. Hansen. Interactive isosurface ray tracing of large octree volumes. In Interactive Ray Tracing 2006, IEEE Symposium on, pages 115 –124, sept. 2006.

# References

[31] Robert Matheson. The electrospace model as a frequency management tool. In Int. Symposium on Advanced Radio Technology, pages 126–132, Mar 2003.

[32] E.M. McIntyre and A. J. Gasiewski. A new technique for detecting the presence of weak interfering digital signals in radiometric noise. In Proceedings of the 2012 International Geoscience and Remote Sensing Symp. (IGARSS), Munich, July 2012.

[33] Michael Neufeld, Ashish Jain, and Dirk Grunwald. Nsclick: bridging network simulation and deployment. WINET: Journal of Wireless Networking, 10(5), Sep 2004. (to appear).

[34] C. Phillips, D. Sicker, and D. Grunwald. Bounding the error of path loss models. In New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on, pages 71–82. IEEE, 2011.

[35] Caleb Phillips, Scott Raynel, Jamie Curtis, Sam Bartels, Douglas Sicker, Dirk Grunwald, and Tony McGregor. The efficacy of path loss models for fixed rural wireless links. In Passive and Active Measurement Conference (PAM), 2011.

[36] J. Riihijarvi, P. Mahonen, M. Petrova, and V. Kolar. Enhancing cognitive radios with spatial statistics: From radio environment maps to topology engine. In Cognitive Radio Oriented Wireless Networks and Communications, 2009. CROWNCOM '09. 4th International Conference on, pages 1 –6, jun. 2009.

[37] H.P. Romero, K.A. Remley, D.F. Williams, C.-M. Wang, and T.X Brown. Identifying RF identification cards from measurements of resonance and carrier harmonics. IEEE Transactions on Microwave Theory and Techniques, 58(7), July 2010.

# References

[38] Dola Saha, Aveek Dutta, Dirk Grunwald, and Douglas Sicker. Active radar - a cooperative approach using multicarrier communication. In IEEE Local Computer Networks, 2010. LCN 2010, 2010.

[39] Dola Saha, Aveek Dutta, Dirk Grunwald, and Douglas Sicker. Gratis: Free bits in the network. Technical Report CU-CS-1075-10, University of Colorado at Boulder, 2010.

[40] A. Sethi and T. X Brown. Hammer model threat assessment of cognitive radio denial of service attacks. In IEEE Dynamic Spectrum Access Networks (DySpAN), Chicago, Oct. 14–17 2008.

[41] Anmol Sheth, Rick Han, Dirk Grunwald, and Douglas Sicker. Mojo: A physical layer anomaly detection mechanism. In ACM MobiSys, 2005.

[42] R. Tandra and A. Sahai. Snr walls for feature detectors. In New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on, pages 559 –570, apr. 2007.

[43] I. Wald, H. Friedrich, G. Marmitt, P. Slusallek, and H.-P. Seidel. Faster isosurface ray tracing using implicit kd-trees. Visualization and Computer Graphics, IEEE Transactions on, 11(5):562 –572, sept.-oct. 2005.

[44] G.S.Woods, A. Ruxton, C. Huddlestone-Holmes, and G. Gigan. High-capacity, long-range, over ocean microwave link using the evaporation duct. Oceanic Engineering, IEEE Journal of, 34(3):323 –330, july 2009.

[45] Y. Zhao, J. Gaeddert, K. Bae, and Reed J.H. Radio environment map enabled situation-aware cognitive radio learning algorithms. In Proceedings of the SDR 06 Technical Conference and Product Exposition, 2006.

# References


[1] J. W. Allen, T. X Brown, D. C. Sicker, and J. Ratzloff. Proc. of the International Symposium on Advanced Radio Technologies. NTIA Special Publication SP-04-409, Springfield, VA, 2004.

[2] E. Anderson, C. Phillips, D. Sicker, and D. Grunwald. Signal quality pricing: Decomposition for spectrum scheduling and system configuration. In New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on, pages 408 –419, may 2011.

[3] Eric Anderson, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. Modeling environmental effects on directionality in wireless networks. Mathematical and Computer Modeling, 2010. To Appear.

[4] Eric Anderson, Gary Yee, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. The impact of directional antenna models on simulation accuracy. In 7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2009.

[5] H. S. Berger, K. R. Kontson, A. E. Leu, T. X Brown, F. Frantz, D. M. Parker, V. Prasad, and D. Stewart. IEEE recommended practice for the analysis of in-band and adjacent band interference and coexistence between radio systems. IEEE Standard P1900.2-2008, 29 July 2008.

[6] J. B. Bernthal, T. X Brown, D. N. Hatfield, D. C. Sicker, P. A. Tenhula, and P. J. Weiser. Trends and precedents favoring regulatory embrace of smart radio technologies. In IEEE Dynamic Spectrum Access Networks (DySpAN), Dublin, April 17–20 2007.

# References


[1] J. W. Allen, T. X Brown, D. C. Sicker, and J. Ratzloff. Proc. of the International Symposium on Advanced Radio Technologies. NTIA Special Publication SP-04-409, Springfield, VA, 2004.

[2] E. Anderson, C. Phillips, D. Sicker, and D. Grunwald. Signal quality pricing: Decomposition for spectrum scheduling and system configuration. In New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on, pages 408 –419, may 2011.

[3] Eric Anderson, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. Modeling environmental effects on directionality in wireless networks. Mathematical and Computer Modeling, 2010. To Appear.

[4] Eric Anderson, Gary Yee, Caleb Phillips, Douglas Sicker, and Dirk Grunwald. The impact of directional antenna models on simulation accuracy. In 7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2009.

[5] H. S. Berger, K. R. Kontson, A. E. Leu, T. X Brown, F. Frantz, D. M. Parker, V. Prasad, and D. Stewart. IEEE recommended practice for the analysis of in-band and adjacent band interference and coexistence between radio systems. IEEE Standard P1900.2-2008, 29 July 2008.

[6] J. B. Bernthal, T. X Brown, D. N. Hatfield, D. C. Sicker, P. A. Tenhula, and P. J. Weiser. Trends and precedents favoring regulatory embrace of smart radio technologies. In IEEE Dynamic Spectrum Access Networks (DySpAN), Dublin, April 17–20 2007.