# Global Environmental MEMS Sensors (GEMS): A Revolutionary Observing System for the 21st Century

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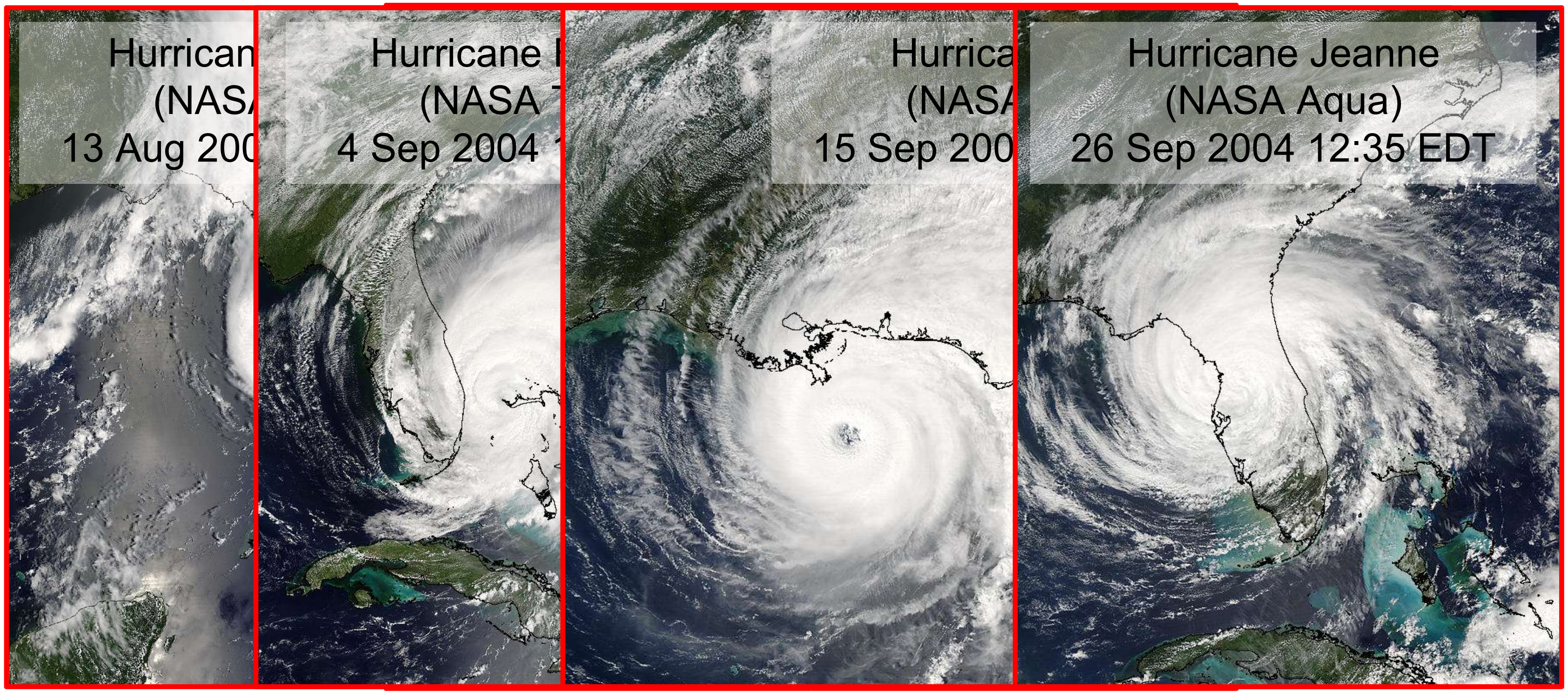
# Outline

- Motivation
- Concept description
- Status of development
  - Key issues
  - Enabling technologies
- Future efforts
- Summary

# Motivation

- Produce environmental observing capabilities commensurate with advances in atmospheric models
  - Mitigate loss of life and property through improved planning / response
  - Improve weather forecasts especially for high impact weather events



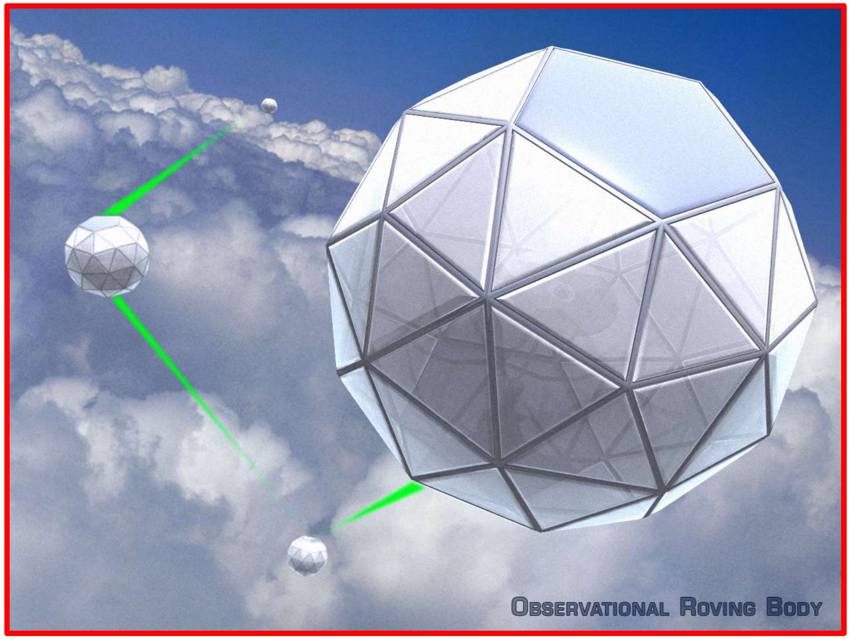
# Motivation

- Produce environmental observing capabilities commensurate with advances in atmospheric models
  - Mitigate loss of life and property through improved planning / response
  - Improve weather forecasts especially for high impact weather events
- Improve density / distribution of in situ observations
  - "Enable entirely new investigations to expand dramatically the understanding of the earth system" (NIAC Grand Challenge)
  - Calibrate remote sensing
- Complement remote sensing
  - Improve vertical / temporal resolution
  - Measure in cloud systems
  - Measure multiple parameters including chemistry
  - "Conduct comprehensive exploration of the solar system through remote sensing, in situ, and sample return" (NIAC Grand Challenge)

# Concept Description

- Integrated system of airborne probes
  - Mass produced at very low per unit cost
  - Disposable
  - Suspended in the atmosphere
  - Carried by wind currents
  - MicroElectroMechanical System (MEMS) and/or nanotechnology-based sensors
- Self-contained with power source for
  - Sensing, geolocation, communication, limited computation
- Mobile, 3D wireless network with communication among
  - Probes
  - Intermediate nodes
  - Data collectors
  - Remote receiving platforms

Broad scalability & applicability



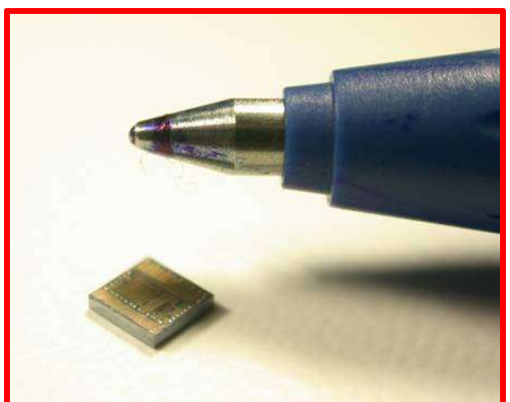
# Key Issues & Enabling Technologies

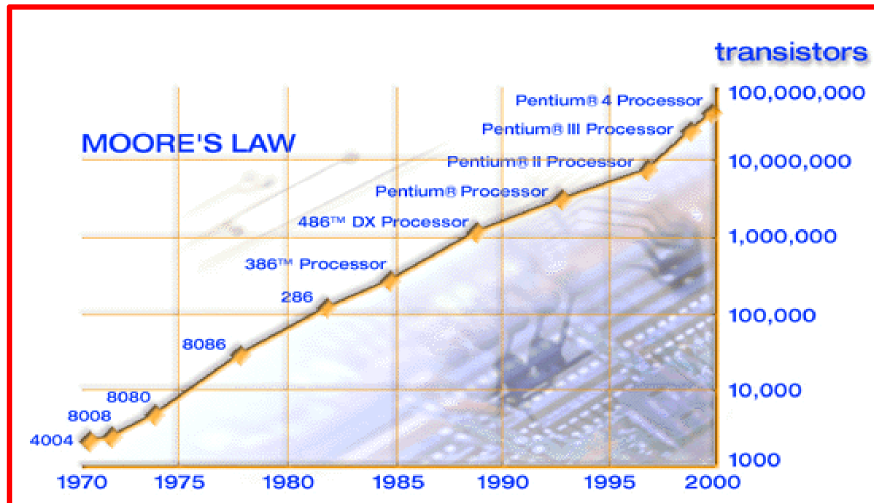
| Issues | Enabling Technologies |
|---|---|
| Probe design | Materials science, micro/nanotechnology |
| Power | Thin film solar cells, super capacitors, batteries, micro fuel cells |
| Communication | Radio Frequency, optical, active and passive methods |
| Networking | Ad-hoc, multi-point to point |
| Signal Processing | GPS, localization, MEMS-based accelerometers, data exfiltration |
| Sensing | MEMS-based pressure, temperature, humidity sensors |
| Deployment/dispersion, scavenging | Numerical weather prediction, Lagrangian particle models |
| Data impact | Observing system simulation experiments |
| Data collection/ management | Artificial intelligence, data mining, ground/space-based infrastructure |
| Environmental | Biodegradable/bioinert materials, organic electronics |
| Cost | Nanotechnology, MEMS mass production, packaging, deployment strategies, networking/data collection infrastructure |

# Probe Form Factor - Miniaturization

## Initial Concept – (dust-sized device)

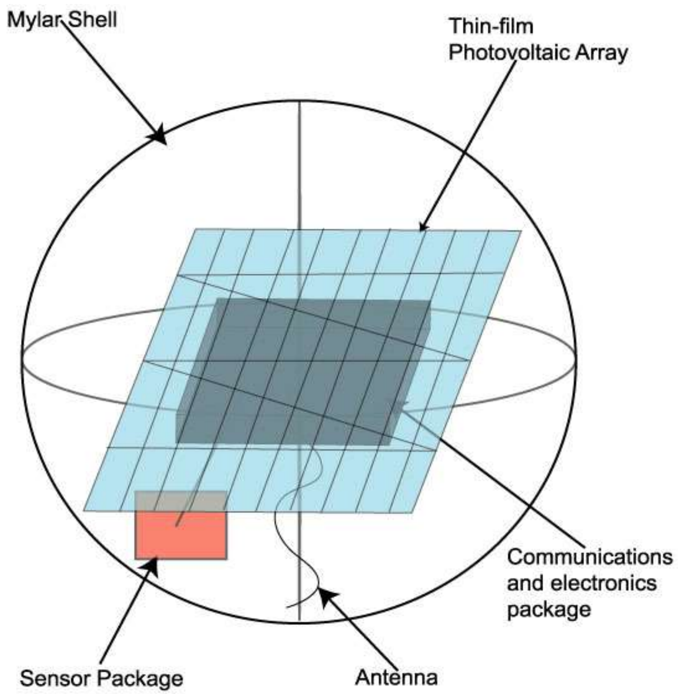
- Full monolithic integration of sensors, communications, & processing yet to be accomplished
- Power technologies do not scale with Moore's law – power density insufficient
- Antenna size proportional to wavelength (10 GHz = 3 cm)
- Small natural objects fall *FAST.* Dandelion seeds $V_t$ = 10 cm $s^{-1}$ with mass of 0.6-0.8 mg



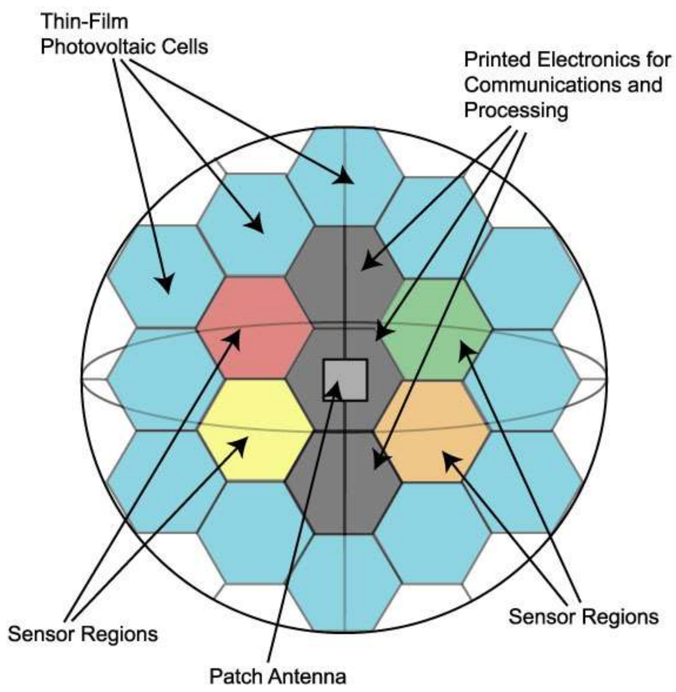


# Probe Design

## Observational Roving Body (ORB)
## Constant pressure vessel




Design 1: enclose COTS electronics inside a helium-filled Mylar™ shell

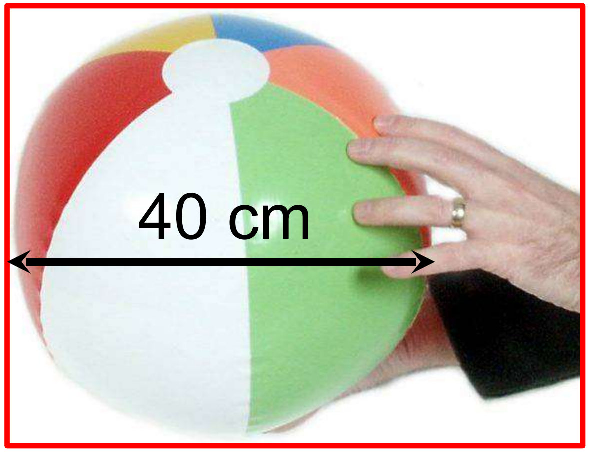



Design 2: embed electronics functionality into the shell

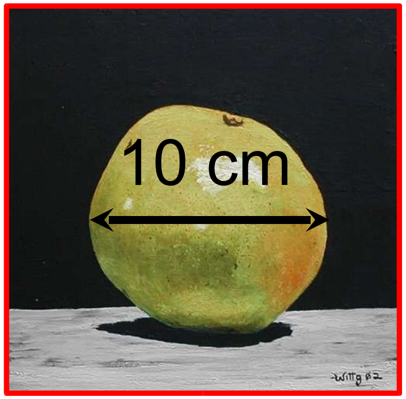
# Probe Attributes

| | Neutral Buoyancy 1 km* | | Neutral Buoyancy 10 km* | |
|---|---|---|---|---|
| Parameter | Design 1 | Design 2 | Design 1 | Design 2 |
| Diameter (cm) | 48 | 10 | 104 | 17 |
| Shell Thickness (μm) | 25 | 1 | 25 | 1 |
| Payload Mass (gm) | 30 | 0.5 | 30 | 0.5 |

*Based on standard atmosphere parameters

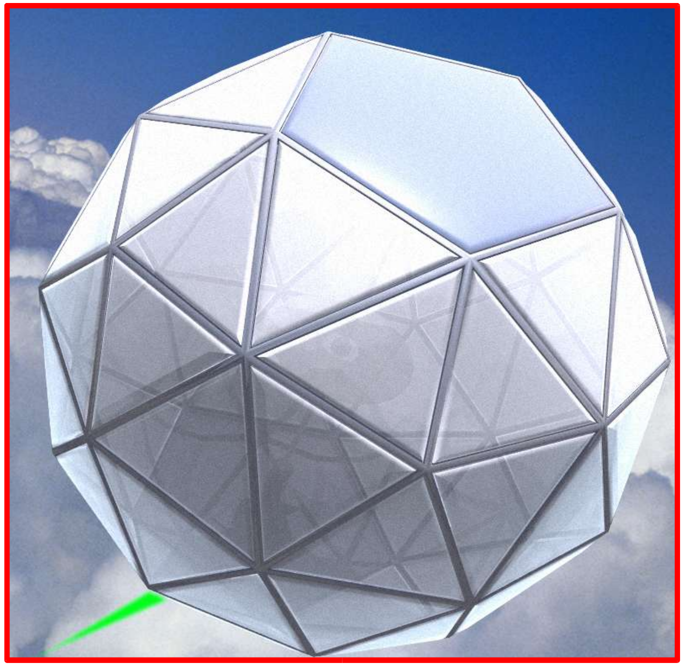






# Probe Shell

- Thickess
  - Tensile strength
  - Mylar™ 5-µm thick burst ~ 7 km
  - Carbon nanotube reinforced polymers – how thin can we make shell?
- Gas permeability
  - 0.4-0.8 months time constant for 1 mil (25-µm Mylar™)
  - Metalize shell & greatly reduce permeability
- Seals / seams
  - Strength
  - Permeability
- Water / ice loading
  - Hydrophobicity via chemical or mechanical design
- Component integration



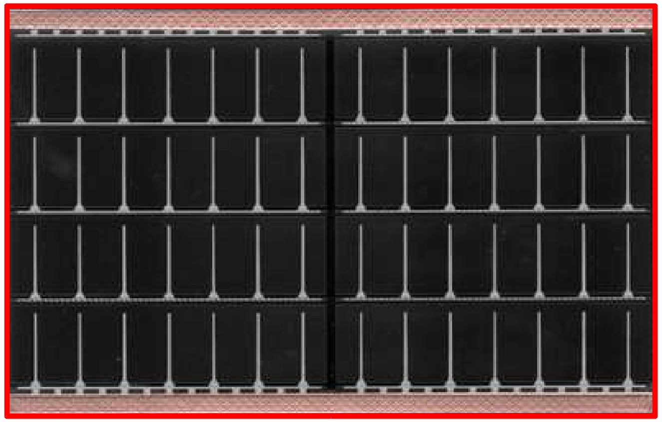
# Probe Component Mass (Design 1)

| *Component* | *Mass (grams)* | *Percent mass (%)* |
|---|---|---|
| Shell | 20 | 40 |
| Thin-film solar cell | 6 | 12 |
| RF probe | 5 | 10 |
| Antenna | 2 | 4 |
| GPS hardware | 10 | 20 |
| Sensors | 2 | 4 |
| Misc. electronics | 5 | 10 |
| **Total** | **50** | **100** |

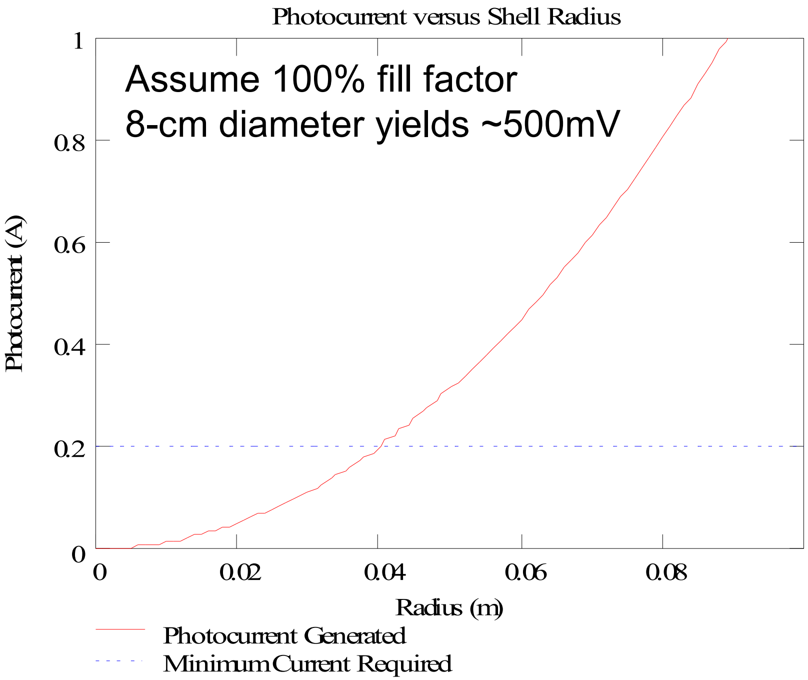
By incorporating the payload functionality into the shell, the probe mass can be reduced dramatically.

# Power Generation

- Thin-film solar cells
  - Commercially available
  - Amorphous silicon (a-Si)
  - Dye-sensitized nanocrystalline solar cells (DYSC)
  - Efficiencies around ~10% but expect ~30% in the next decade



a-Si Thin-film solar cell from Iowa Thin Film Technologies



# Power Storage

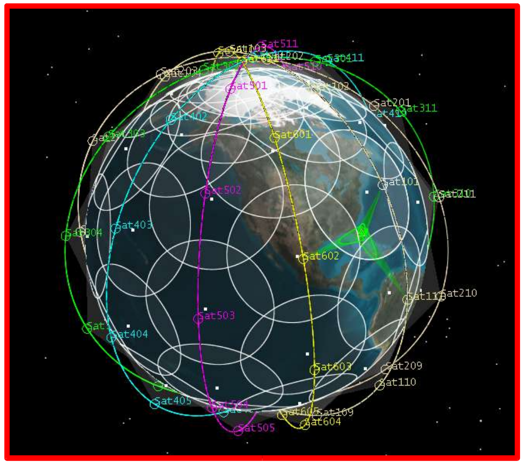
- Super/ultra capacitors (electrochemical double layer)
  - Commercially available
  - Thin-film based devices
  - Efficiently store electrical charge for extended periods of time
  - Charged/discharged many times with no adverse effects

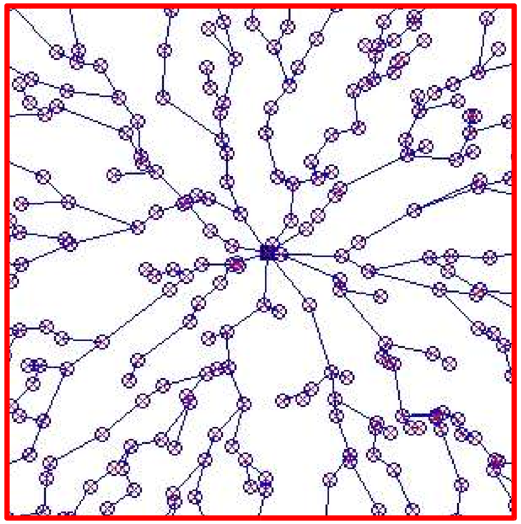

| | Battery | Super Capacitor |
|---|---|---|
| Typical Lifetime [years] | 5 | 30 |
| Efficiency [%] | 70-85 | 85-98 |
| Ease of Charging | Damage risk | No current limit |
| Discharge | Varies | Gradual |
| Environmental Pollutants | Li or other metal | Inert |

- Power budget trade offs
  - Efficiency of solar cells
  - Electronics (frequency & distance for communication)
  - Number of super capacitors
  - Mass / size

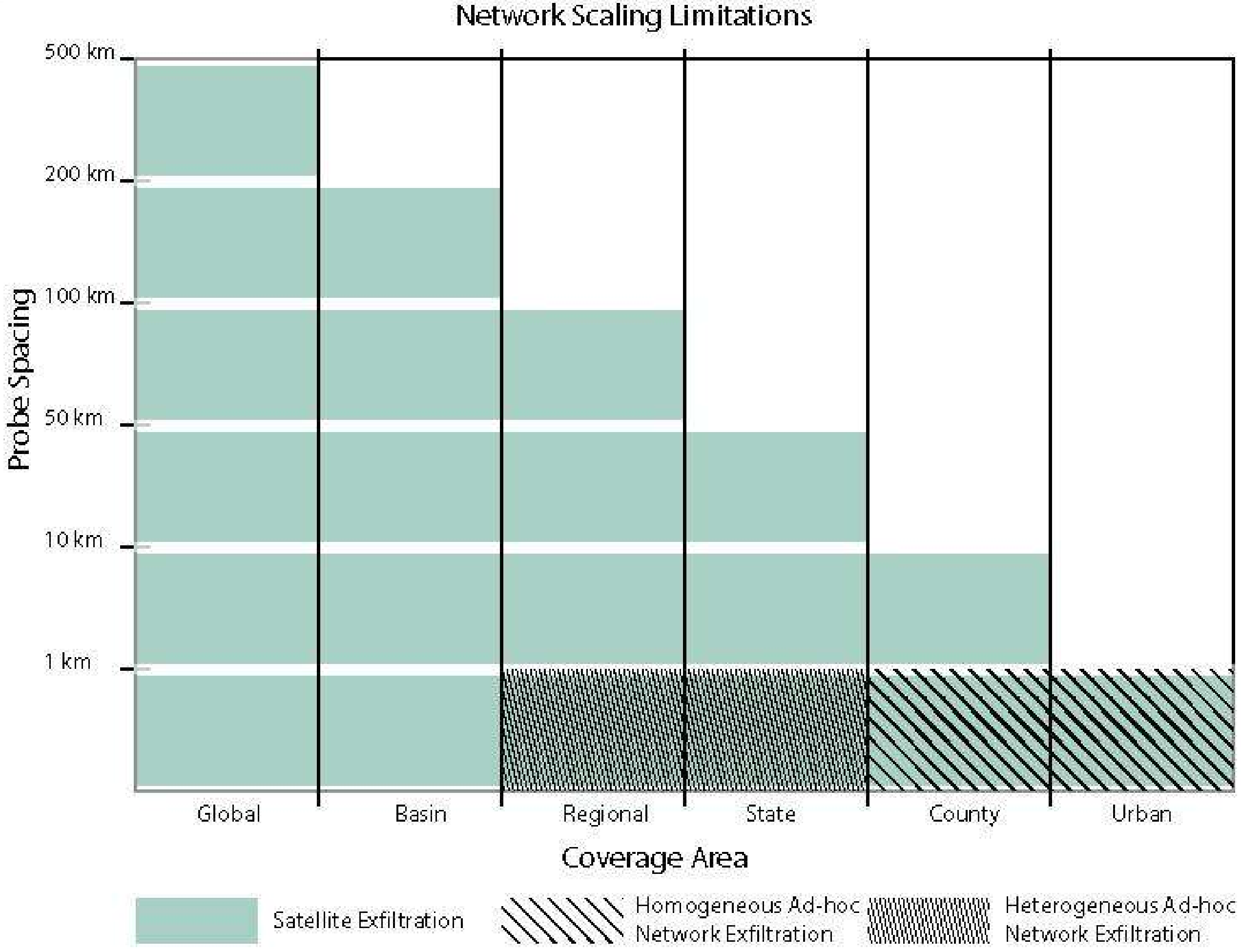
# Worldwide Network/Communications Options

- RF-based
- Satellite Constellation
  - Probes directly send discrete data packets to LEO satellite(s) for collection
- Mobile Ad hoc Network
  - Data packets hop through mobile network to distributed exfiltration nodes
- Hybrid
  - Combination of the two depending upon probe location and conditions





# Network Scaling – Exfiltration



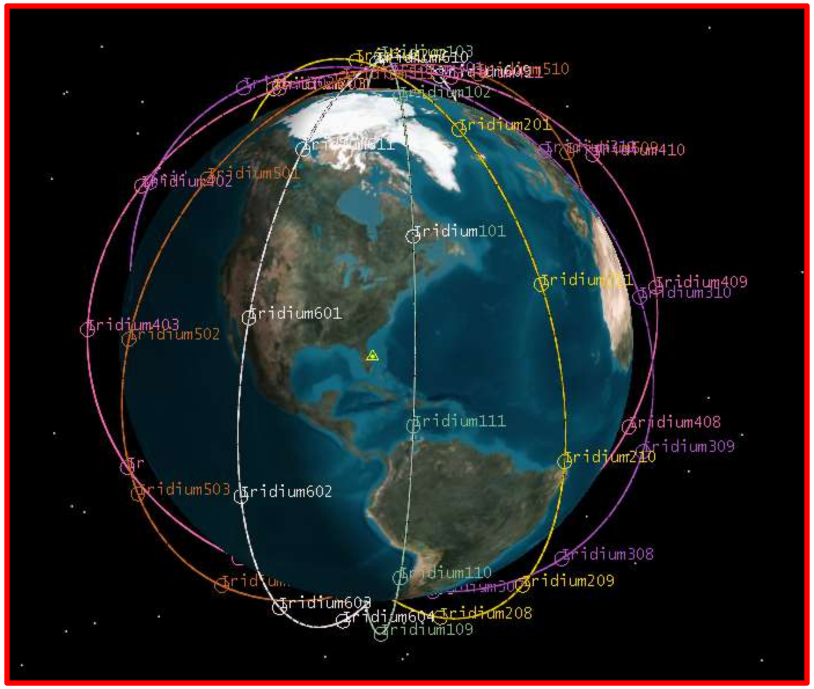
# Total Worldwide Data Throughput

- Approximate Network Throughput
  - Message size : $Total_{bits}$= ~90 bits + (n-1)*68 bits
  - $10^6$ Active Nodes → 110 kbps (99 bits/900 sec)
- Overall network bandwidth is well within the capabilities the Iridium constellation or similar
  - Ad hoc networks will require sub-dividing the throughput to multiple ground stations

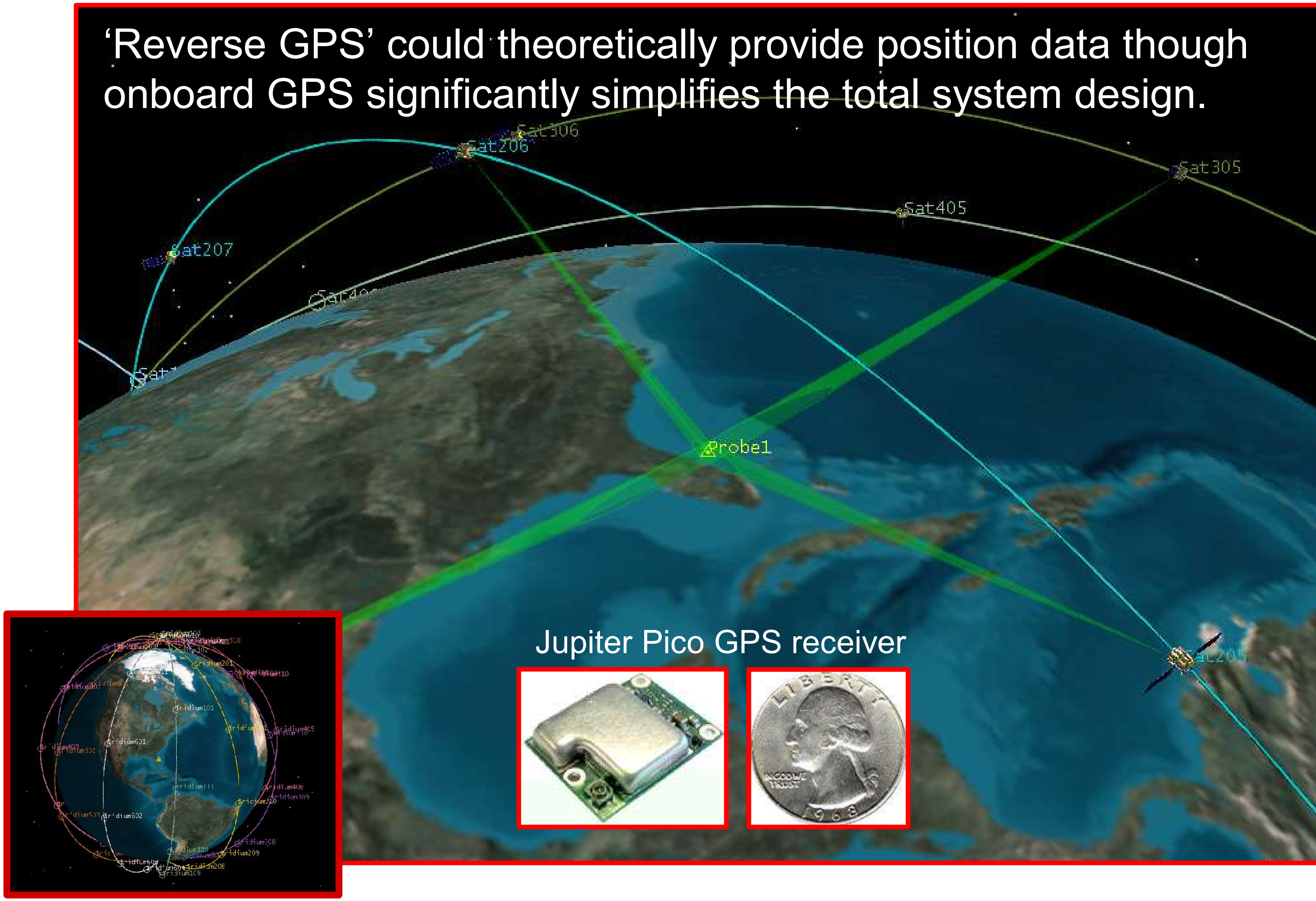
| | Dynamic Range | Accuracy | Resolution | Full Bits | Compressed | Notes |
|---|---|---|---|---|---|---|
| SensorID | 1 to $10^6$ | N/A | 1 part in $10^6$ | 20 | 14 | Probability of common < 0.1% |
| Latitude | $-90^o$ to $+90^o$ | +/- 100m | 1 part in 180,000 | 18 | 9 | Maximum Separation/Travel < 75 km |
| Longitude | $0^o$ to $360^o$ | +/- 100m | 1 part in 180,000 | 18 | 9 | Maximum Separation/Travel < 75 km |
| Altitude | -1 to +20 km | +/- 100m | 1 part in $10^5$ | 7 | 7 | |
| Time | $t_0 + 10^7$ sec | +/- 10 sec | 1 part in $10^5$ | 17 | 6 | Maximum Δt = 15 minutes |
| Temperature | -50 to +40 °C | +/- 1°C | 1 part in 45 | 6 | 4 | Temperature altitude model |
| Pressure | 50 to 1050 mb | +/- 1 mb | 1 part in 500 | 9 | 7 | Pressure altitude model (20%) |
| Humidity | 10 to 100% | +/- 5% | 1 part in 9 | 4 | 4 | |
| **Total** | | | | **99 bits** | **60 bits** | **Round-off error will propagate in compressed data after each hop.** |

# Satellite Constellations

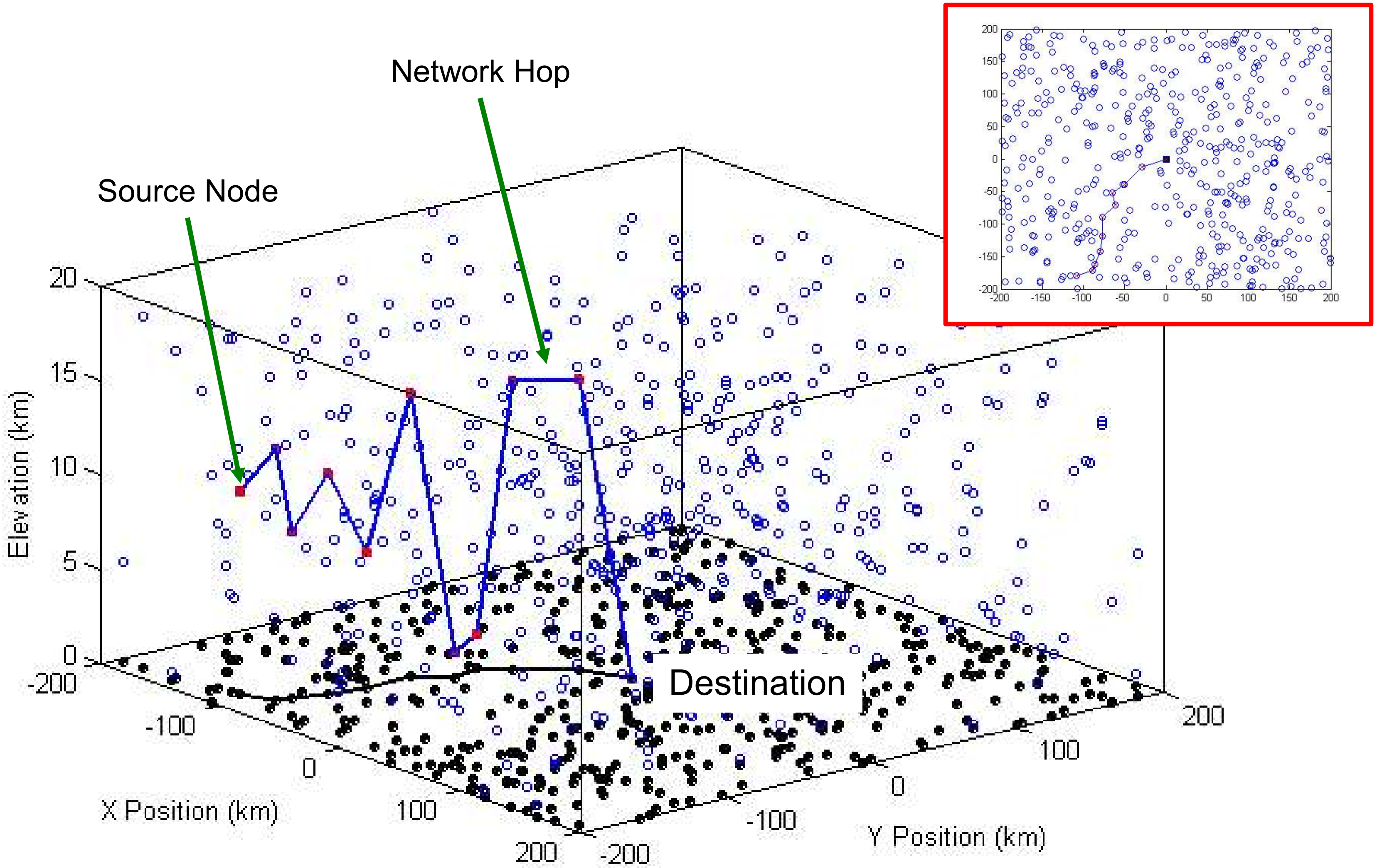
- Globalstar
  - 48 Satellites in 6 Orbital Planes
    - Altitude : 1414 km
  - Development Cost : $2.5B
  - Coverage limited to areas with ground stations to which the satellites can directly downlink.
- Iridium
  - 66 satellites in 6 orbital planes
    - Altitude : 750 km
  - Development Cost : $4.7B
  - Inter-satellite links allow for truly global coverage.
  - The low orbital altitude and global coverage could be used to directly exfiltrate GEMS data.
    - Optimum performance from modified network and custom protocol.
    - Reduced # of satellites with periodic coverage passes could reduce costs though limit extensibility.



# Iridium-Like Satellite Link



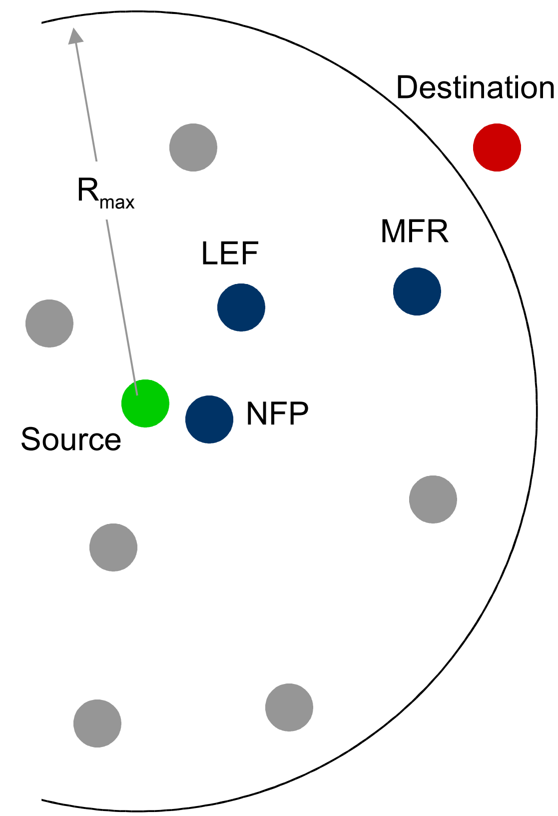
# Mobile Ad hoc Network Data Extraction



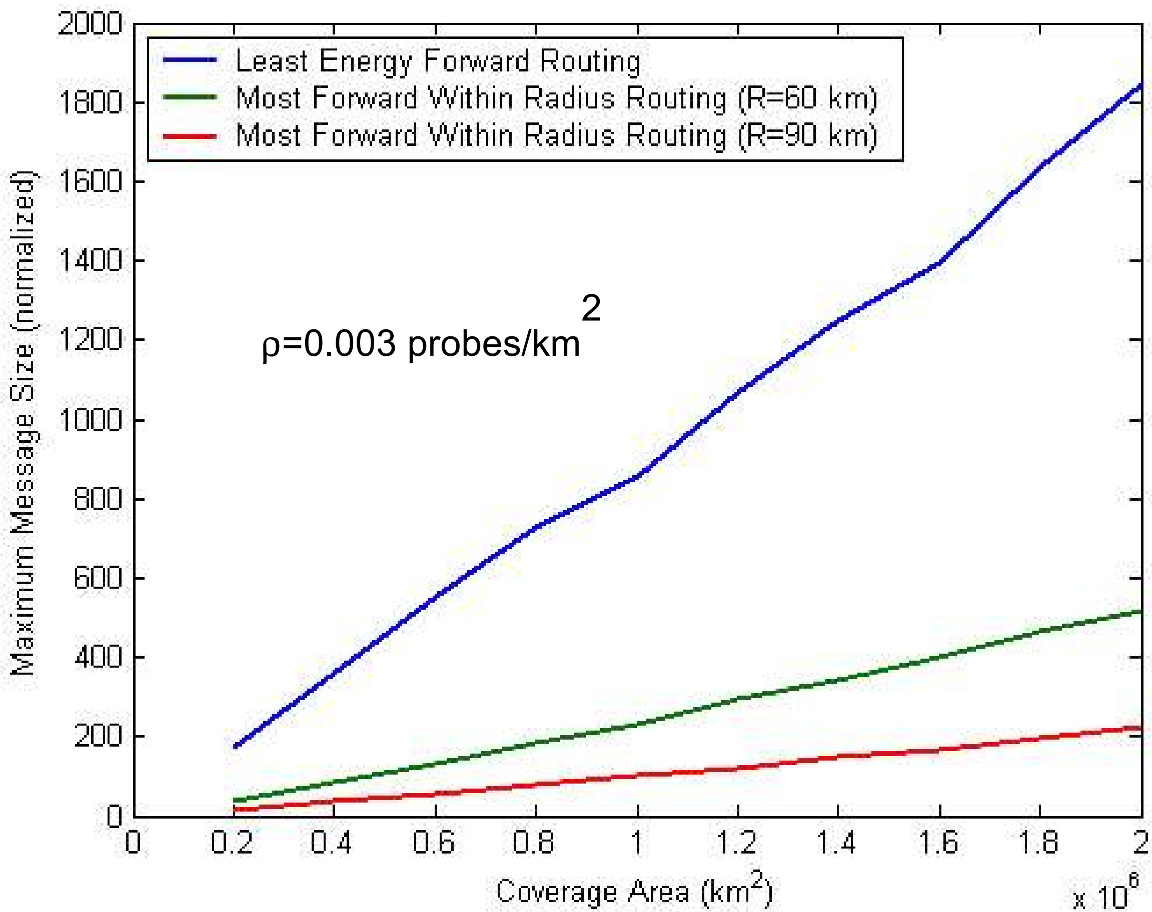
# Position Based Routing Options

- Routing
  - Each node acts as a data source & information router to a common base station
    - Sequence : receive message, append own data, transmit forward
    - All nodes know location of base station (all for some location service)
- Some Greedy Routing Techniques
  - Most Forward within Radius (MFR)
    - Data packet transmitted to the probe within reach which is closest to the final destination
  - Nearest Forward Progress (NFP)
    - Data packet transmitted to the nearest probe which resides closer to the final destination
    - Utilizes transmission power modification to achieve reduced energy consumption
  - Compass Routing
    - Packet sent to to node within range closest to home vector
  - Least Energy Forward (LEF)
    - Data is transmitted to the probe which locally minimizes the energy required to move towards the target (Joules/meter)
    - Variation of NFP & Compass Routing
- Globally Optimal Routes (# hops, energy, lifetime in network)
  - Greedy routing produces locally optimal routes which are not necessarily optimum over the entire route.
  - Adding message feedback to globally optimize routes introduces a significant penalty in mobile networks with low data traffic.

**Local Greedy Choices**



# Routing Method Comparison (2 x $10^6$ $km^2$ / base station)




U.S. (48)

- Area = 8.6x$10^6$ $km^2$
- Min stations : 5

Northern Hemisphere

- Area = 255x$10^6$ $km^2$
- Min stations : 128

# Data Extraction Comparison

- Least Energy Forwarding (LEF) has superior performance in smaller networks
- From a worst case probe energy perspective, direct satellite transmission is preferable for larger networks (> 100 nodes)
- Future modeling (remainder of phase II, year 2) will include cost in the utility model to determine the optimal technique (including hybrid approaches)

| | LEF | MFR (R=60 km) | MFR (R=90 km) | Iridium Like |
|---|---|---|---|---|
| Typical Transmission Distance (km) | 14.5 | 51.7 | 81 | 2000 |
| Average Messages Routed | 35 | 9.8 | 5.97 | 1 |
| Average Messages Routed on Last Hop | 987 | 269 | 114 | 1 |
| Relative Energy Requirements (Typical Probe) | 1.0 | 3.6 | 5.3 | 1.1 |
| Relative Energy Requirements (Last Hop) | 28.2 | 97.7 | 101.6 | 1.1 |
| Notes | 1,2 | 1,2 | 1,2 | 2,3 |

1. Number of probes = 6000 per reporting area (~$2 \times 10^6$ km$^2$)
2. Relative energy based on simple $r^2$ propagation model
3. Assuming 24 dB of additional antenna gain on receiver and 3 dB of gain on probe

# Data Impact Issues

- Dynamic simulation models
  - ARPS (Advanced Regional Prediction System)
  - LPM (Lagrangian Particle Model)
- Virtual weather scenarios
  - Cost effective & controlled method to explore parameter space
- Deployment scenarios & dispersion patterns
- Simulated probe data & statistics
- OSSE (Observing System Simulation Experiments)

# Potential Deployment Strategies

- High-altitude (stratospheric) balloons
  - Global Atmosphere-Ocean IN-situ System (GAINS)
  - StratSats (Global Aerospace NIAC phase II project)
- Rawinsonde (weather) balloons (Sep 99, Jan/Jun/Dec 01)
- Surface release w/ positive buoyancy
- Unattended Aerial Vehicles
  - Military applications
  - Civilian applications
    - Global Universal Profiling System (GUPS); http://www.fsl.noaa.gov/gups/
    - Hurricane reconnaissance
- Commercial aircraft
- Field experiments
- Directly from spacecraft or during planetary mission

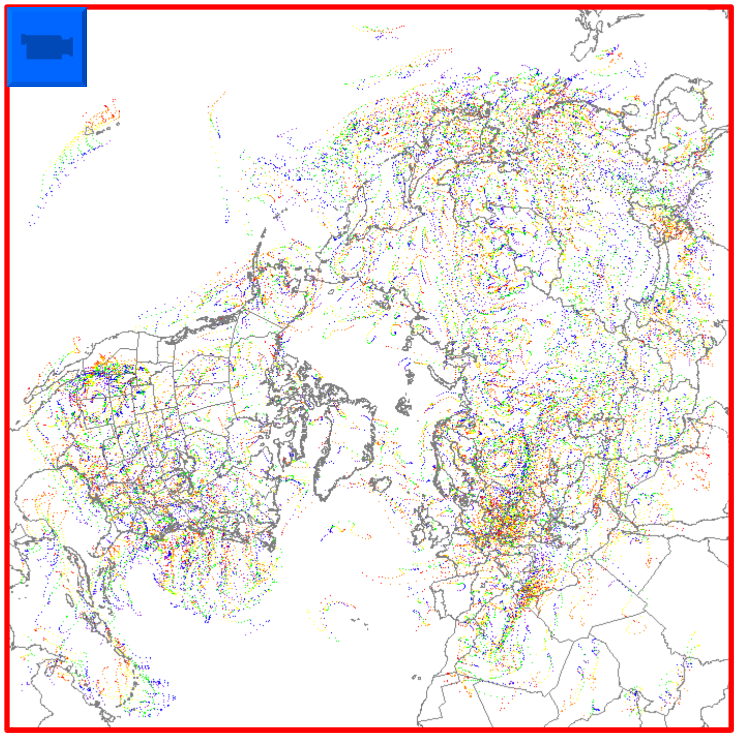
# Deployment Parameters

| | **Rawinsonde or Weather Balloons** | **Surface Release w/ Buoyancy Control** |
|---|---|---|
| Number of sites | ~950 @ current release stations over land (NH) | ~12,000 @ current surface stations (NH) |
| Altitude | ~2 to 17 km every 450 m | 0.03 - 15 km |
| Frequency | 12 h | 4 h |
| Duration (June 2001) | 30 days | 30 days |
| Terminal Velocity ($v_t$) | *Average 0.006 m $s^{-1}$ | 0.0 m $s^{-1}$ at level of neutral buoyancy |
| Total probes released | 1,592,640 | 2,154,780 |

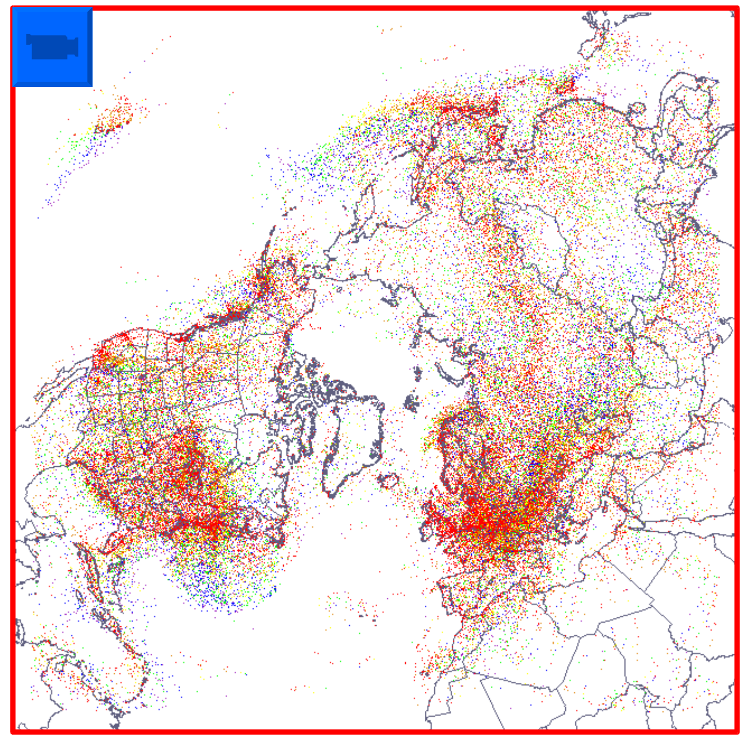
* $V_t$ is density dependent

# Dispersion Patterns

Rawinsonde Release



Surface Release



<2.5

2.5-5

5-7.5

7.5-10

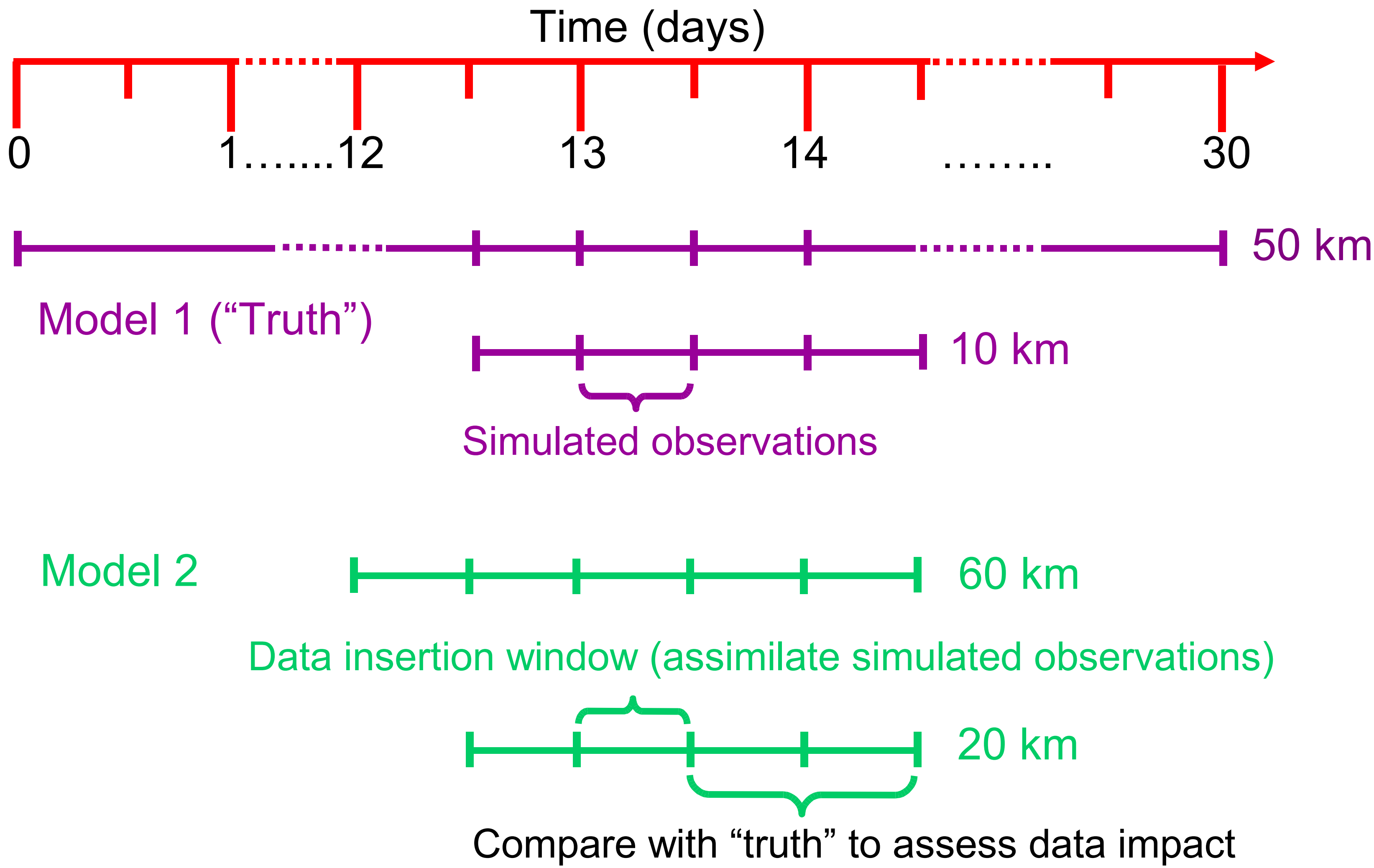
10-12.5

12.5-15

>15

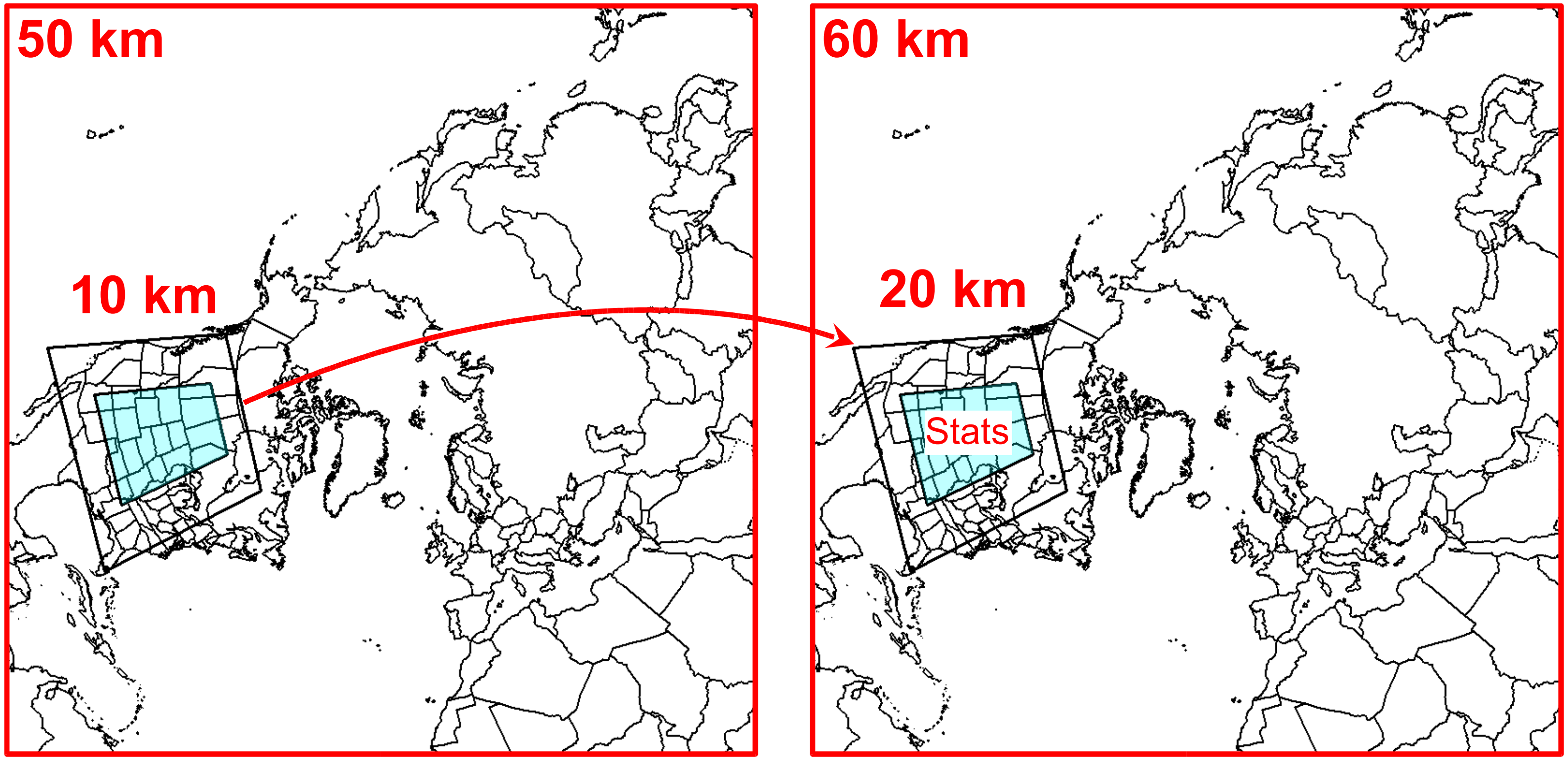
0000 UTC 1 June 2001 Initialization
Probe altitude (km) given by color scale

# Observing System Simulation Experiments (OSSE)



# Simulation Domains

Same boundary & initial conditions



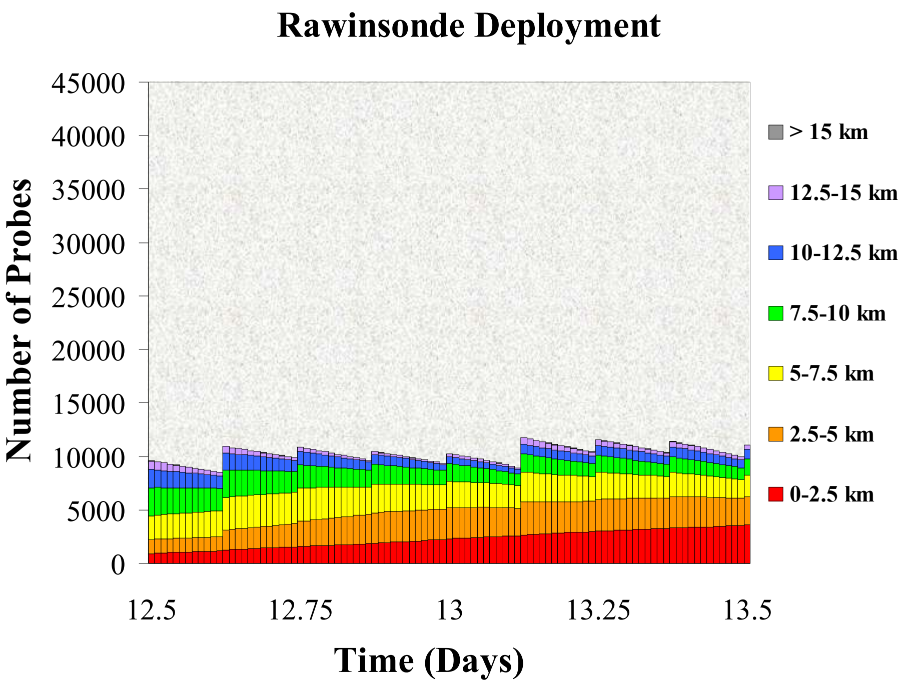

Model 1 ("Truth")

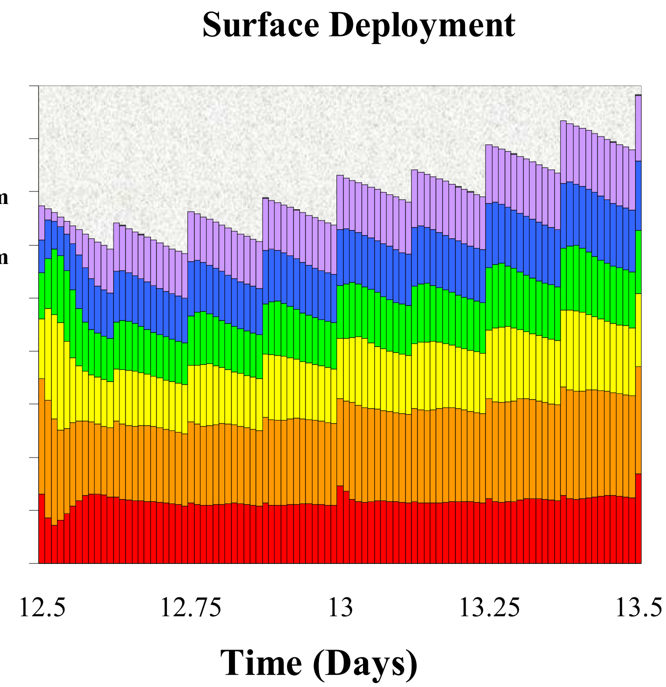
Summer / winter case

Probes deployed / dispersed for 30 days

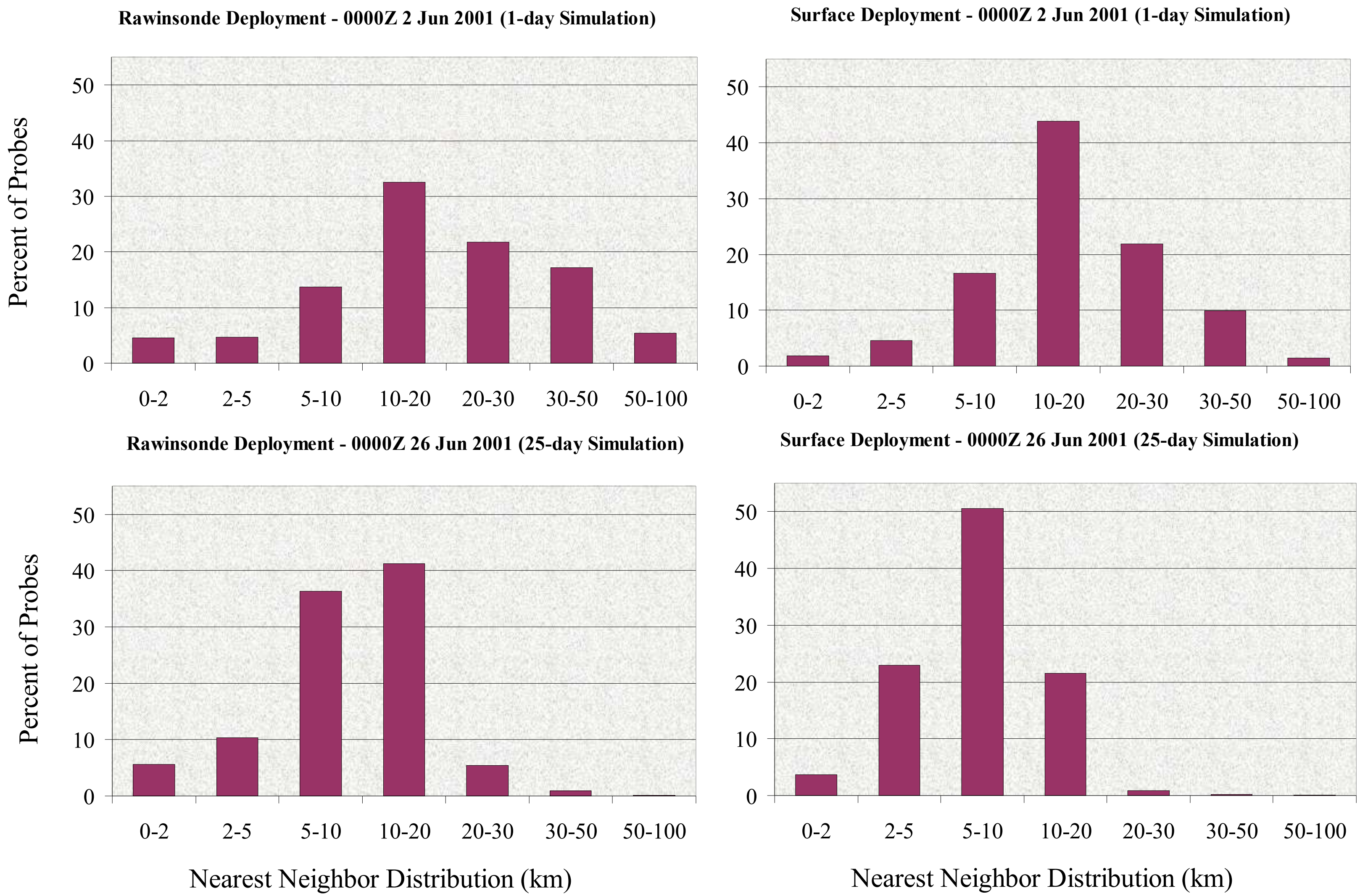
Model 2

# Dispersion Statistics (Regional Domain)

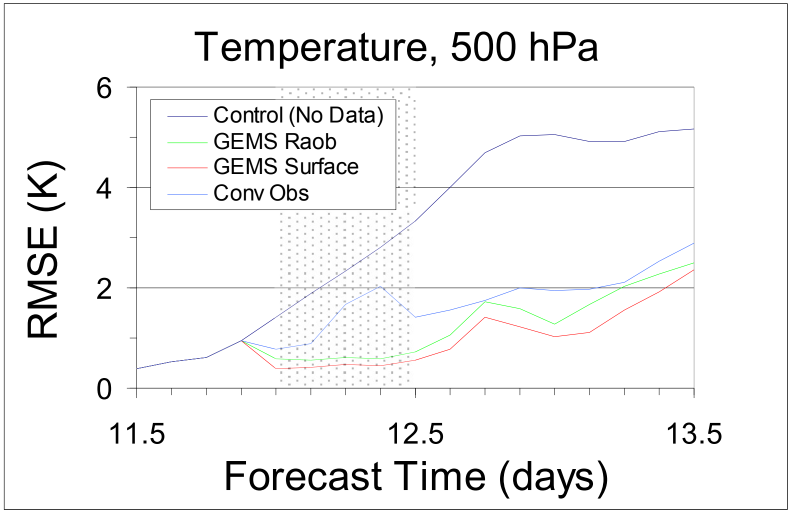


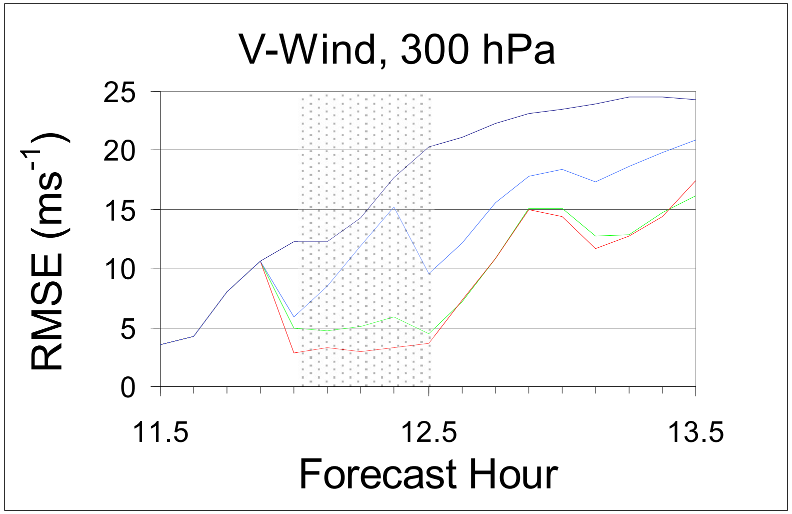



# Dispersion Histograms (Regional Domain)



# Preliminary OSSE Results




OSSEs conducted using Model 2
2-day forecasts from 1200Z 12 June – 1200Z 14 June 2001
Data assimilation performed every 3 h for 12-period (shown by shading)

Control (no additional data)
GEMS Raob (GEMS data from balloon deployment)
GEMS Surface (GEMS data from surface deployment)
Conv Obs (current conventional surface and upper air measurements)

# Future Efforts (NIAC Phase II)

- Power
  - Finalize power budgets (using primarily thin film solar cells & super capacitors)
  - Adaptive power management
- Communications & Networking
  - Continue modeling study of network hierarchy including cost
  - Evaluate network architectures including possible hybrid solution with heterogeneous nodes
- Data Impact
  - Perform sensitivity experiments (deployment scenario, precipitation scavenging, data density, assimilation period, observation accuracy, measurement type)
  - Repeat for winter case
  - Assess impact over longer time periods
- System Model
  - Link different sub-models to maximize overall utility in trade studies
- Technology Roadmap
  - Define system
  - Identify all required enabling technologies
  - Establish milestones for meeting targets
  - Chart single or multiple paths for development based on application

# Future Efforts (Beyond NIAC Phase II)

- NASA Research Announcement Instrument Incubator Program ESTO (suspense 2 Nov 2004)
  - Propose 3-year effort for limited GEMS demonstration
- Related concepts & white papers
  - Probe shell design (materials programs)
  - Airborne Network for Video Imaging, Localization and Surveillance (ANVILS)
  - Threat cloud assessment (chemical & biological characterization)
  - Network for Embedded Tagging, Tracking and Sensing (NETTS)
  - Detection of Littoral Foes via In Situ Networks (DOLFIN) – oceanographic application

# New ENSCO Business Area

- Focus
  - Cutting-edge R&D of airborne-release, wireless probes and probe networks that integrate micro and nanoscale technologies for environmental, defense, intelligence, and space applications
- Goals
  - Project 100% growth first 3 years (R&D programs)
  - Develop prototypes within 2 years
  - Build interdisciplinary team
  - Draw from universities, laboratories, & companies
  - Establish strategic partnerships / collaborations
  - Aggressive management / protection of IP

# Acknowledgments

- Universities Space Research Association
  NASA Institute for Advanced Concepts
  - Phase I funding
  - Phase II funding
- ENSCO, Inc.
  - CEO, Mr. Paul Broome, III
  - President, Mr. Greg Young
  - VP of Strategic Business Development, Dr. John Warburton
  - Board of Directors

# Summary

- Motivation
- Concept description
- Highlight status of phase II GEMS effort
  - Enabling technologies
  - Progress on studying major feasibility issues
- Future plans (year 2 and beyond)