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

**NIAC Phase I CP-01-02**

**John Manobianco,**
**Randolph J. Evans, Jonathan L. Case, David A. Short**
**ENSCO, Inc.**

**Kristofer S.J. Pister**
**University of California Berkeley**

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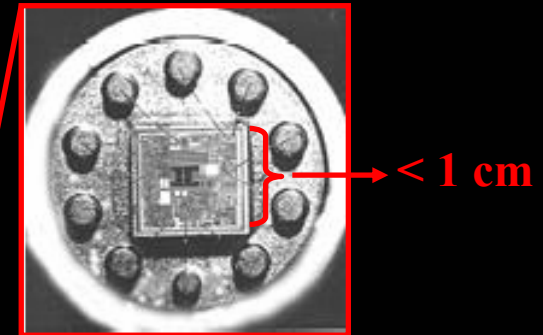
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# Briefing Outline

- Introduction / definitions
- Description
- Motivation
- Major feasibility issues
- Phase II plans
- Summary

# What are MEMS?

- Micro Electro Mechanical Systems (MEMS)

- Micron-sized machines + IC

- Sample applications



< 1 cm





CF96010

# GEMS Concept

Integrated System of airborne probes

- MEMS sensors measure T, RH, P, & V (based on changes in probe position)

- Each probe self contained with power source to provide sensing, navigation, & communication

- Mobile, wireless network with communication among probes & with remote in situ stations, satellites
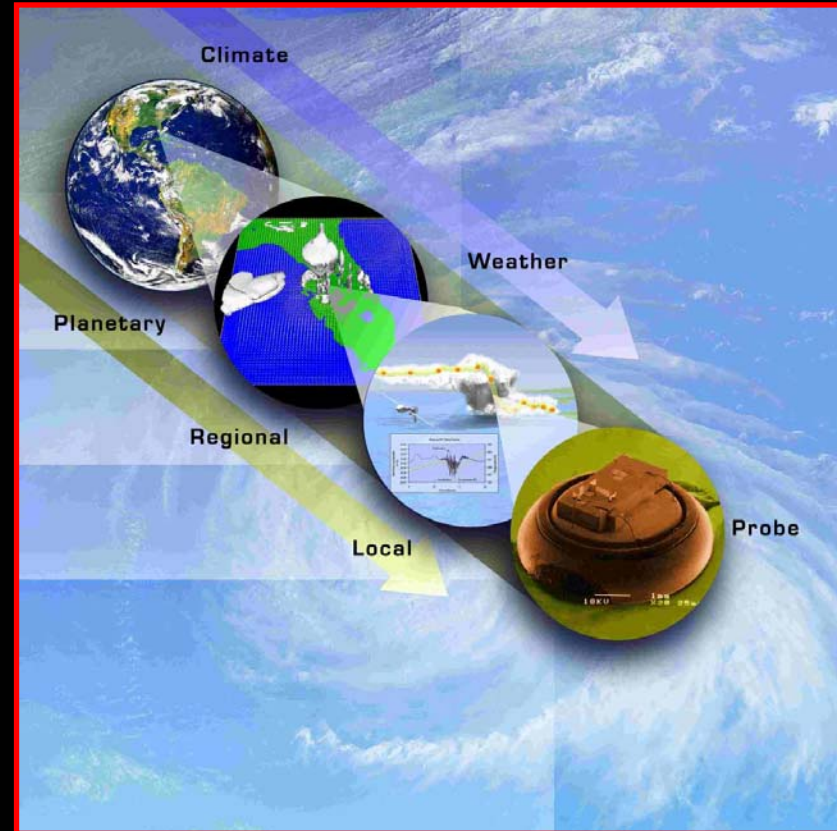


Provide quantum leap in our understanding of the Earth's atmosphere
Improve forecast accuracy well beyond current capability

# Motivation

- ~$2 Trillion of U.S. economy is weather sensitive
- Produce observing capabilities commensurate with advances in atmospheric models
- Overcome limitations of remote sensing
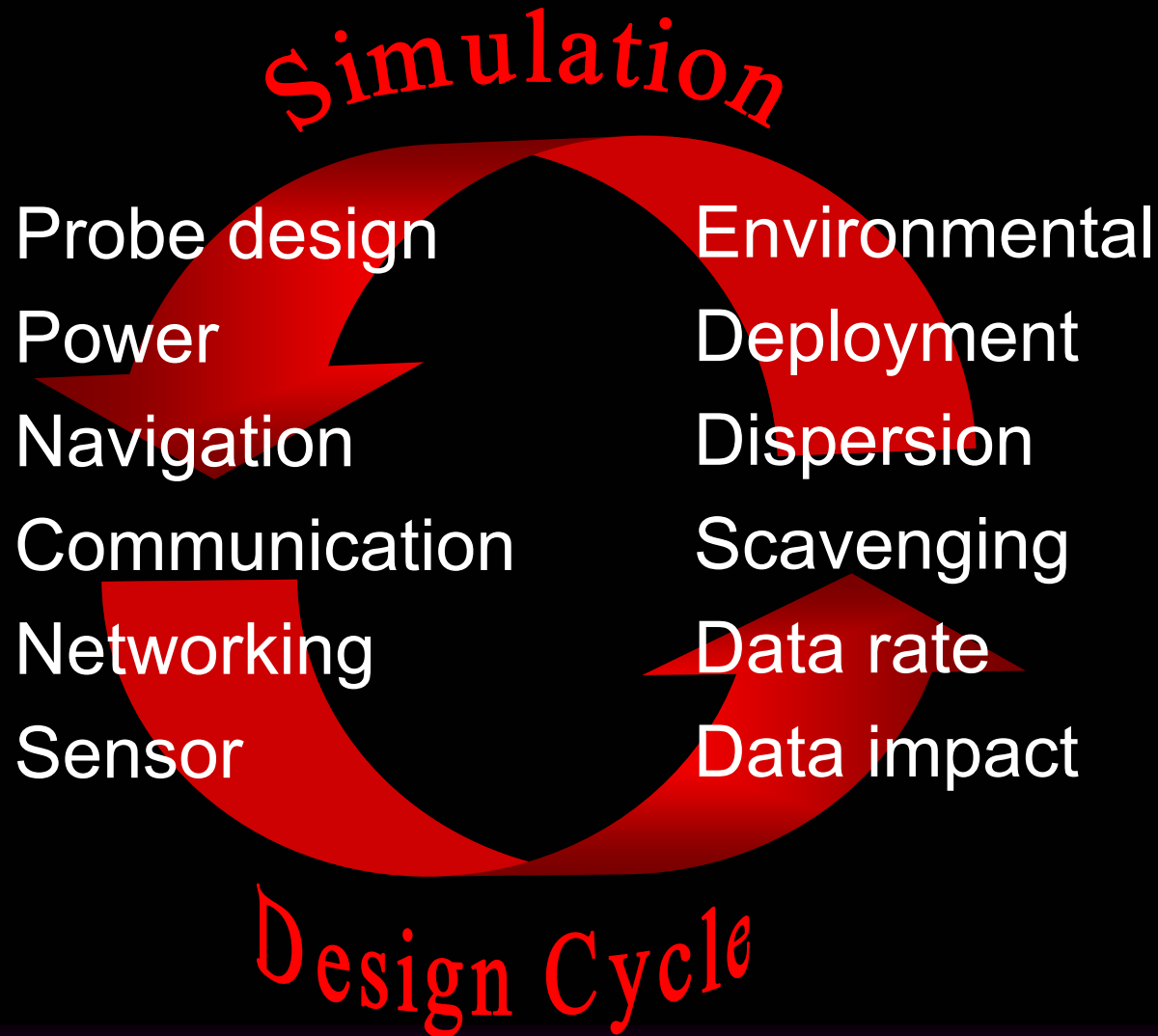- Improve density / distribution of in situ obs

Shuttle Challenger

Jan. 1986

Sept. 1983

Tropical S

(Jun

# Major Feasibility Issues



Simulation

Probe design      Environmental

Power      Deployment

Navigation      Dispersion

Communication      Scavenging

Networking      Data rate

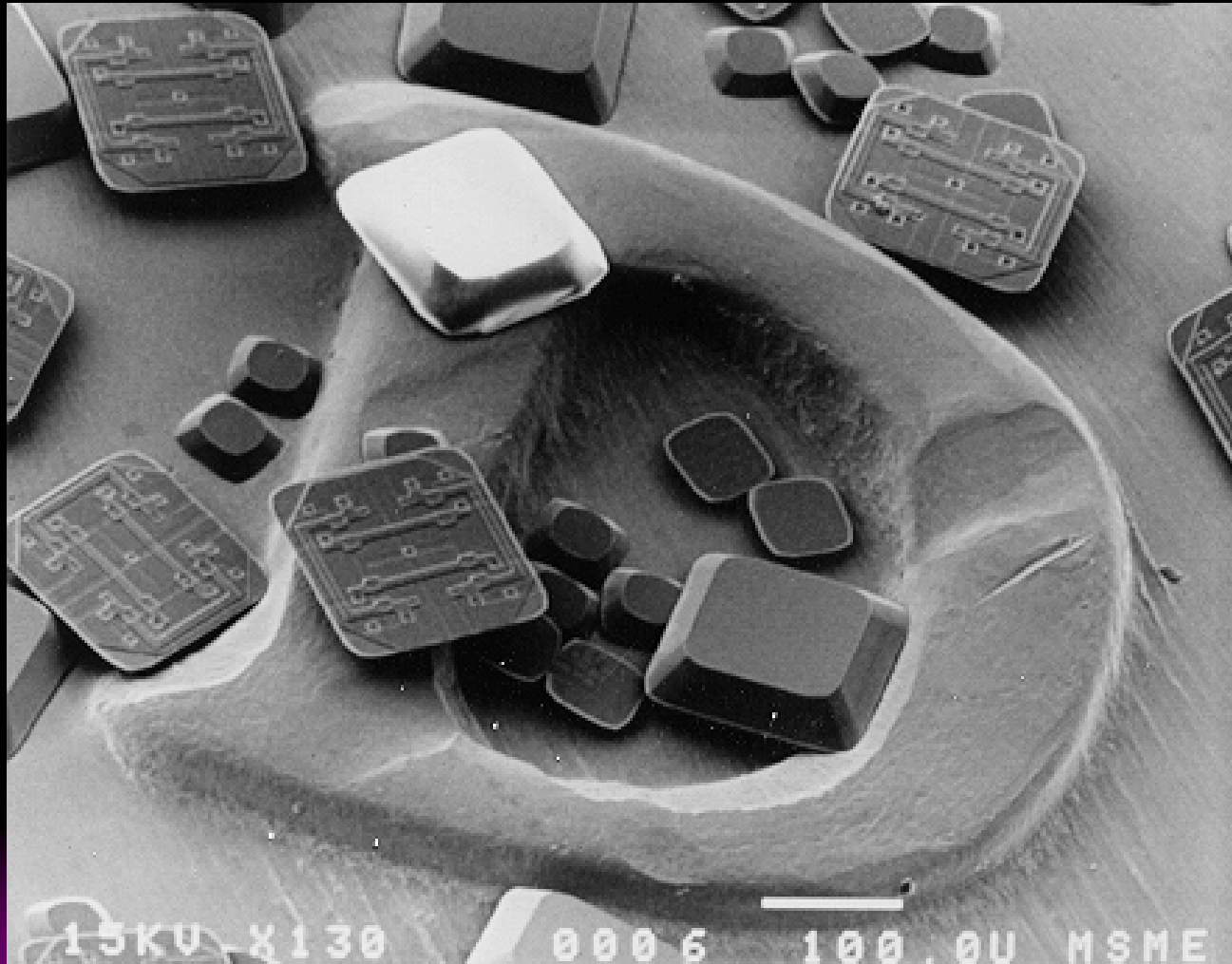Sensor      Data impact
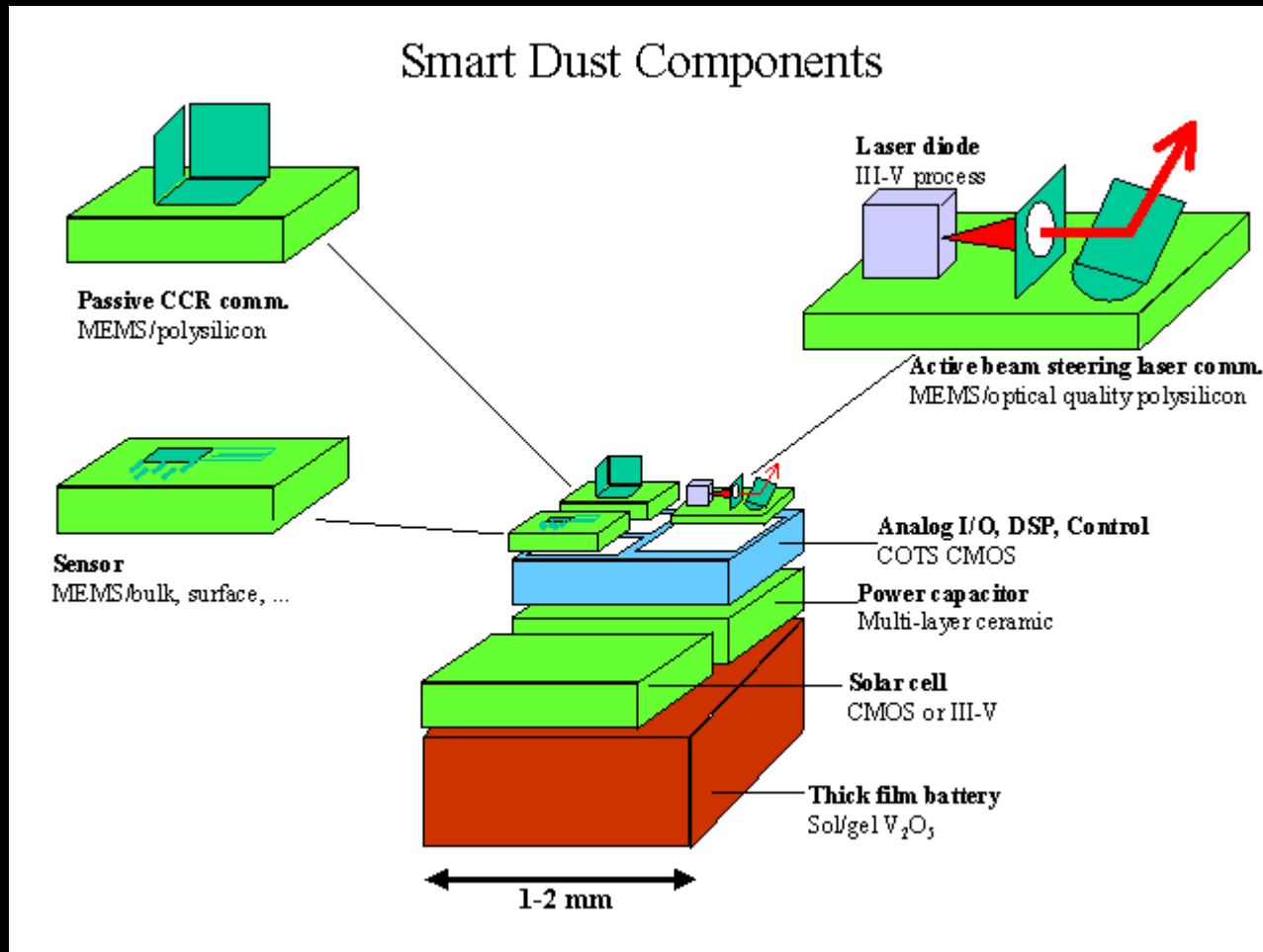
Design Cycle

# Probe design

- Sensing
- Computation
- Communication
- Power

# Moore's Law, take 2

- Nanochips on a dime (Prof. Steve Smith, EECS)

# Smart Dust project



Smart Dust Components

Passive CCR comm.
MEMS/polysilicon

Laser diode
III-V process

Active beam steering laser comm.
MEMS/optical quality polysilicon

Sensor
MEMS/bulk, surface, ...

Analog I/O, DSP, Control
COTS CMOS

Power capacitor
Multi-layer ceramic

Solar cell
CMOS or III-V

Thick film battery
Sol/gel $V_2O_5$

1-2 mm

# Smart Dust control chip



330μm

ambient light sensor
**Photodiode**

**ADC**
100kS/s
2uW

**Sensor input**

**Oscillator**

13 state
**FSM**
controller

**Power input**

TX Drivers
0-100kbps
CCR or diode

**Power**

**Optical Receiver**
1 Mbps, 11uW

**Sensing:**            20 pJ/sample
**Computation:**     10 pJ/instruction
**Communication:** 10 pJ/bit (optical)
                             1000 pJ/bit (RF)

Solar Cell Array   CCR

XL

CMOS IC
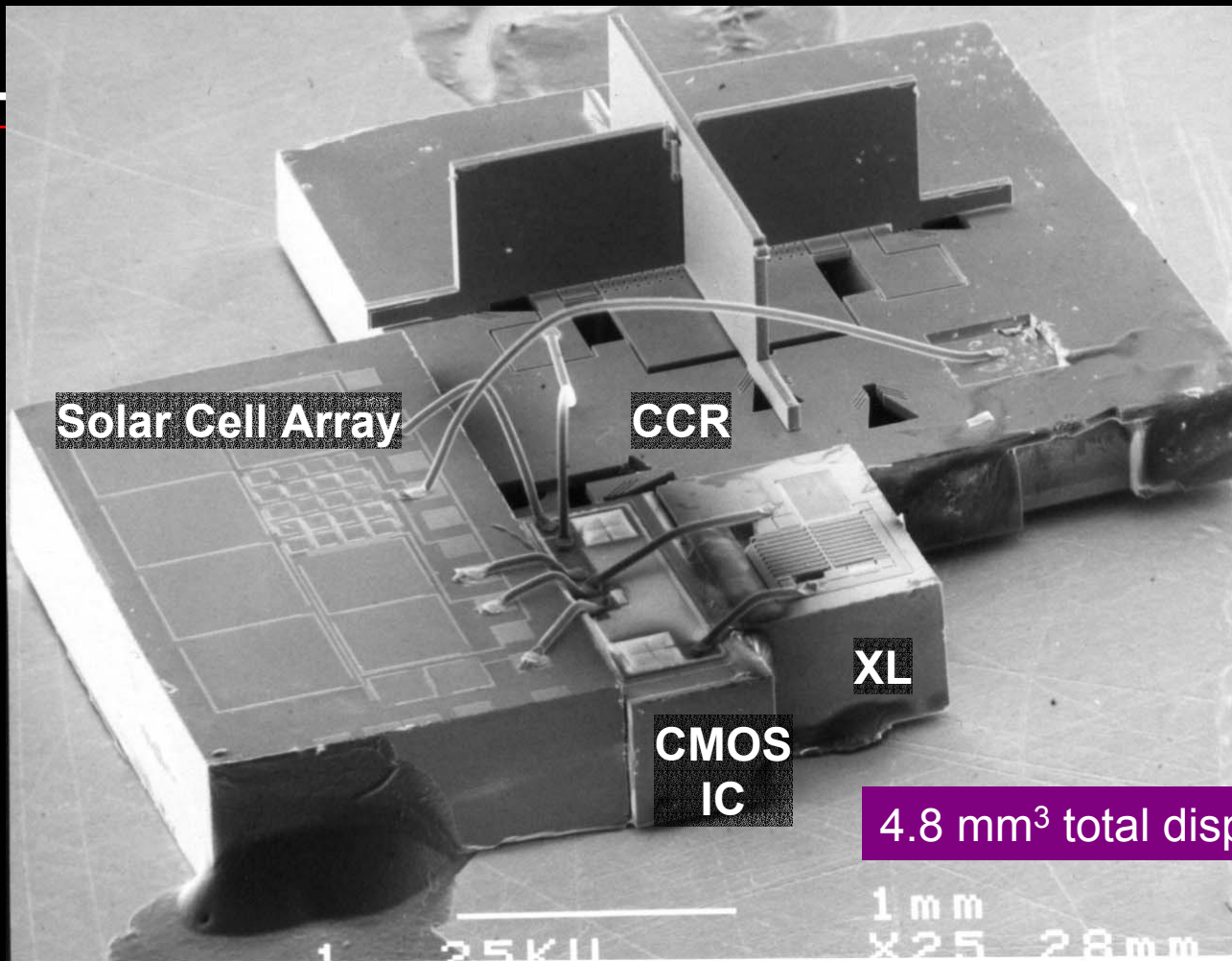
4.8 mm$^3$ total displaced volume

1 mm
25KU X25 28mm

| SENSORS | ADC | FSM | RECEIVER |
|---------|-----|-----|----------|
| PHOTO | 8-bits | | 375 kbps |

OPTICAL IN

| TRANSMITTER |
|-------------|
| 175 bps |

OPTICAL OUT

1V   1-2V   1V   1V   3-8V   2V

SOLAR POWER
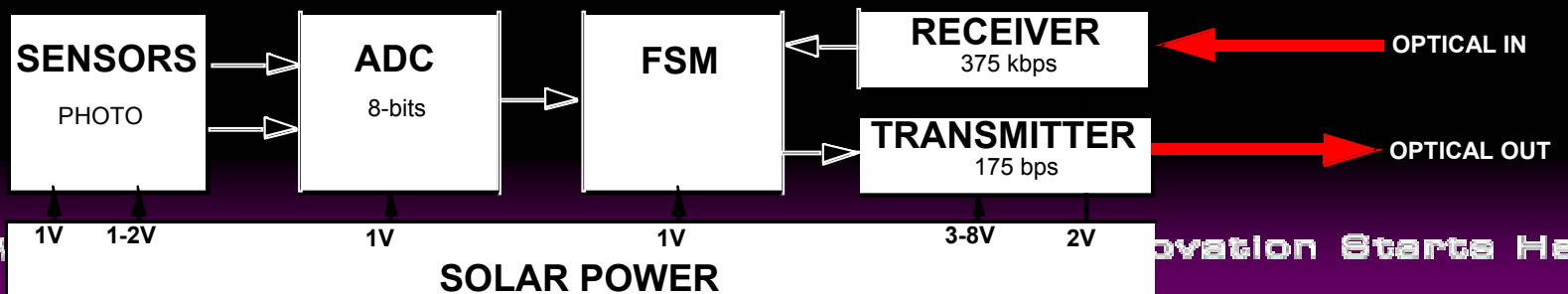
# ~8mm³ laser scanner

Two 4-bit mechanical DACs control mirror scan angles.

~6 degrees azimuth, 3 elevation
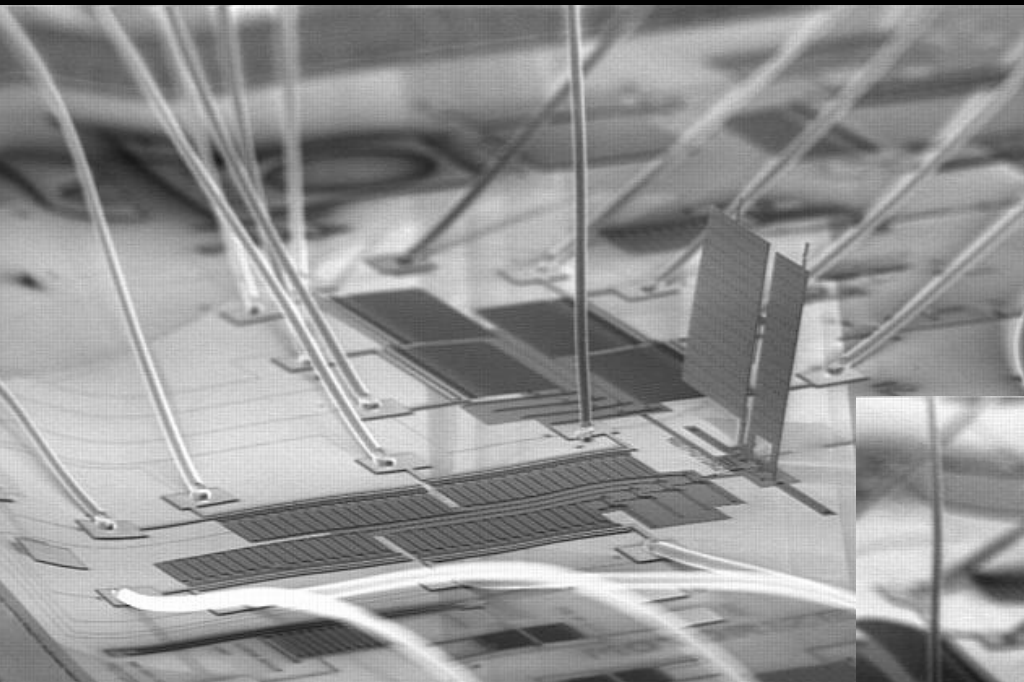
1Mbps



MAG = 39 X    200µm    EHT = 5.85 kV    Signal A = SE2    Date :5
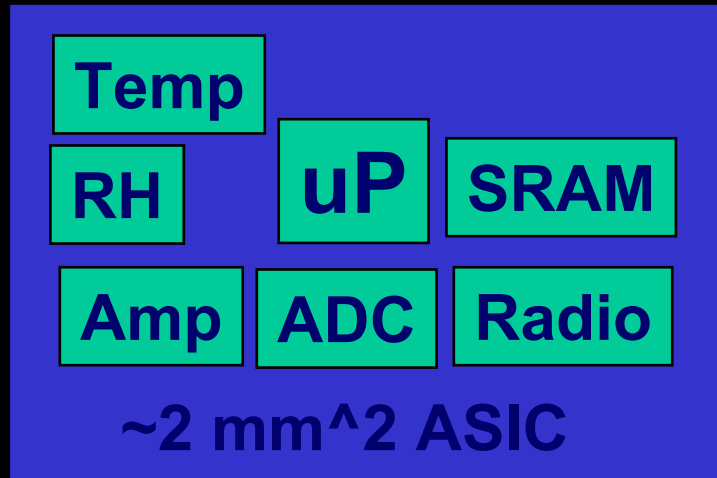                        WD = 35 mm       Photo No. = 832   Time :1



MAG = 37 X    200µm    EHT = 5.85 kV    Signal A = SE2    Date :5 Jan 2000
                        WD = 34 mm       Photo No. = 830   Time :13:42

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# RF probe – in fab

- CMOS ASIC
  - 8 bit microcontroller
  - Custom interface circuits
- 4 external components

**antenna**

**Temp**

**RH**  **uP**  **SRAM**

**Amp**  **ADC**  **Radio**

**~2 mm^2 ASIC**
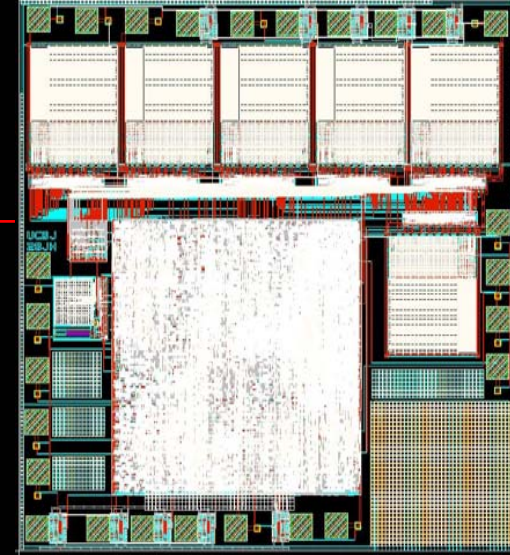
**~$1**

**inductor**

**crystal**

**battery**

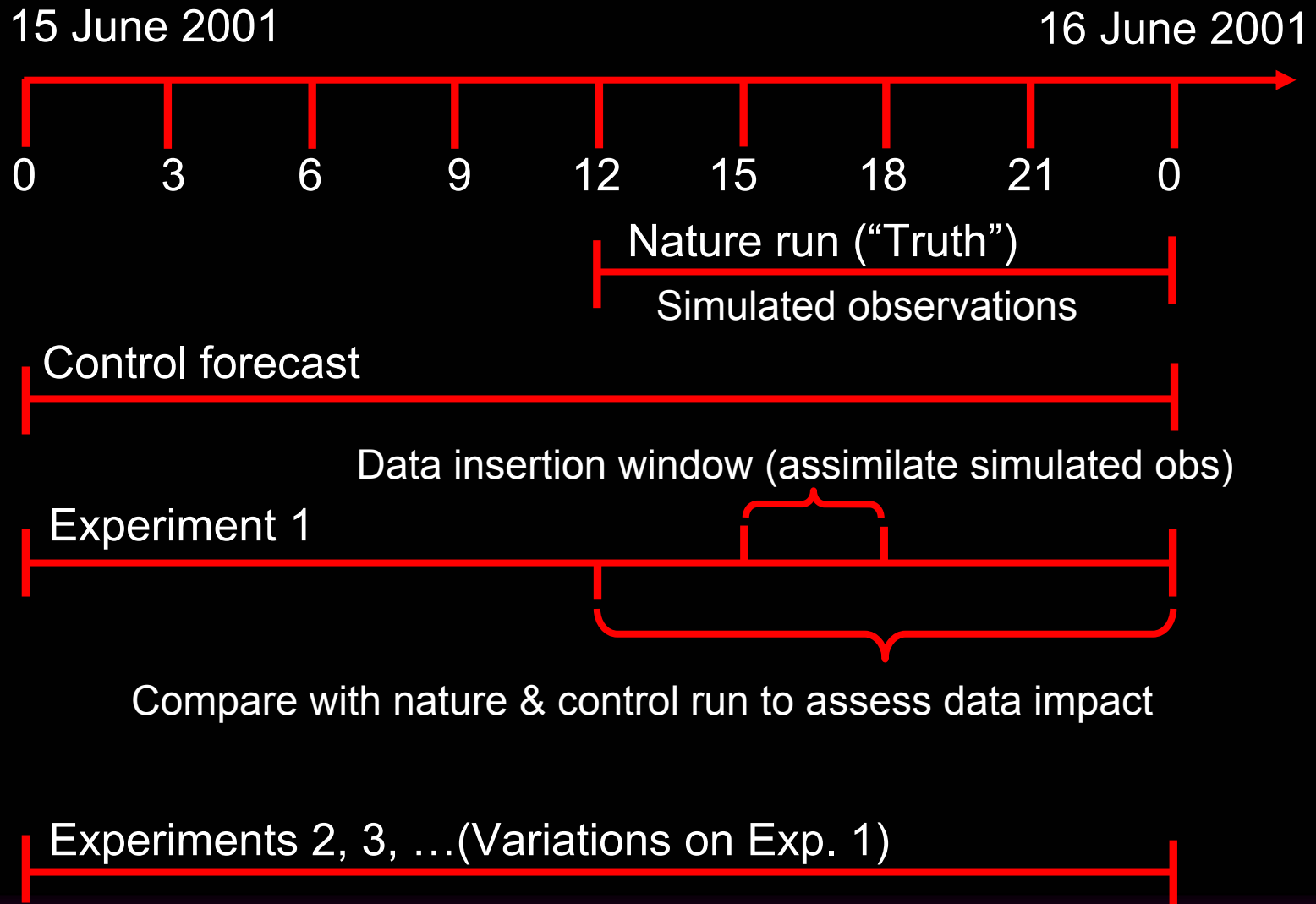# Technology Forecast

- 1 year - $50 node
  - 3 cc, 1 month lifetime (battery)
  - 1' helium balloon deployment
  - 3 km communication range
  - Temp, pressure, humidity
- 3 years - $5/node
  - 1cc, 3 month lifetime (battery)
  - Range/localization
  - Gas sensing
- 10 years - $1/node
  - 10 mm$^3$, 1month lifetime (Aluminum/air battery)
  - Integrated bouyancy control
- 20 years - $0.10/node
  - 1mm, indefinite lifetime (solar + hydrogen fuel cell)
  - GPS/satellite comm

# Simulation Tools

- Numerical weather prediction model
  - Advanced Regional Prediction System (ARPS)
    - Navier-Stokes equations for atmospheric flow
    - Comprehensive physics
  - Virtual weather scenarios
  - Variable spatial & temporal resolution
- Lagrangian particle model
  - Probe deployment & dispersion
  - Simulate turbulence, terminal velocity, etc.

# Observing System Simulation Experiments (OSSE)

15 June 2001                                                      16 June 2001

| 0 | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 0 |

Nature run ("Truth")

Simulated observations

Control forecast

Data insertion window (assimilate simulated obs)

Experiment 1

Compare with nature & control run to assess data impact

Experiments 2, 3, …(Variations on Exp. 1)

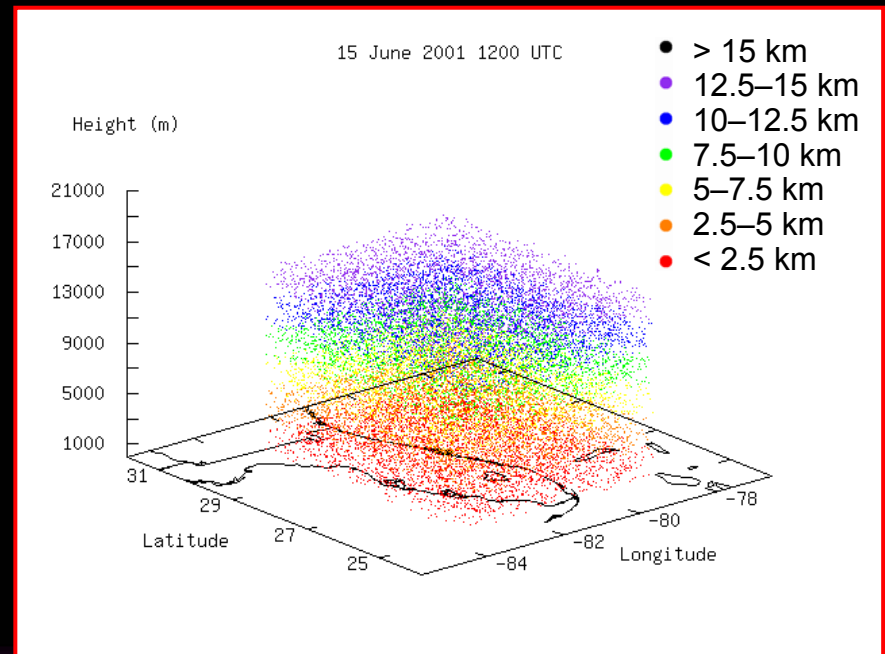# Simulation Domains

Deployment strategy: random in 3D
Deployment period: 6 h from 1200-1800 UTC
Initial mean separation distance:  3.5 ± 1.3 km
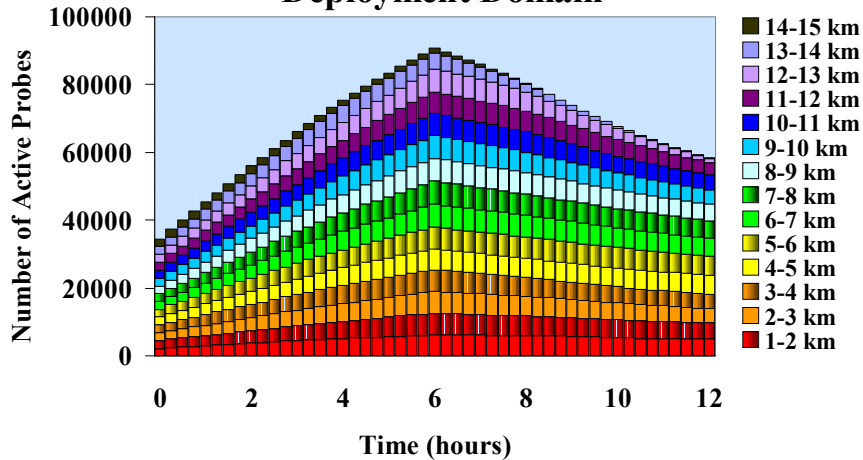Terminal velocity: 0.08 m s$^{-1}$
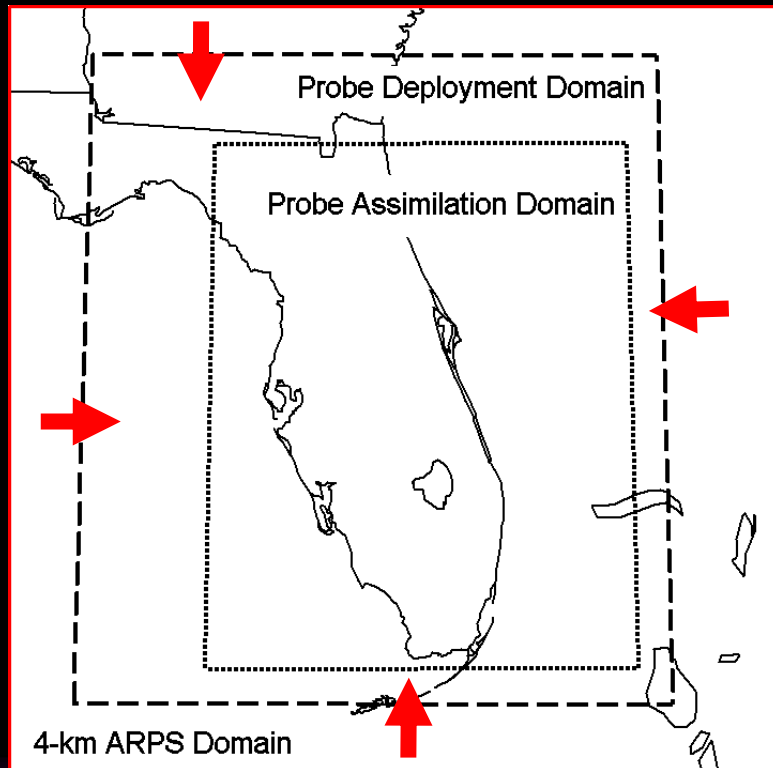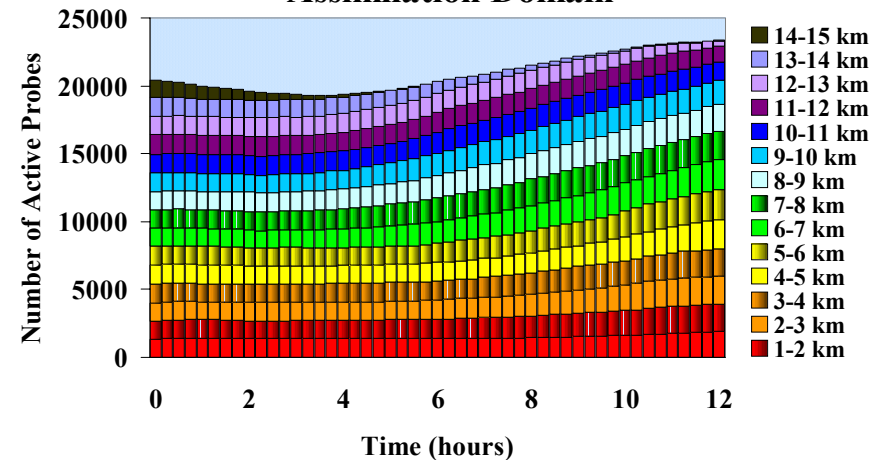


Initial 3D Probe Distribution
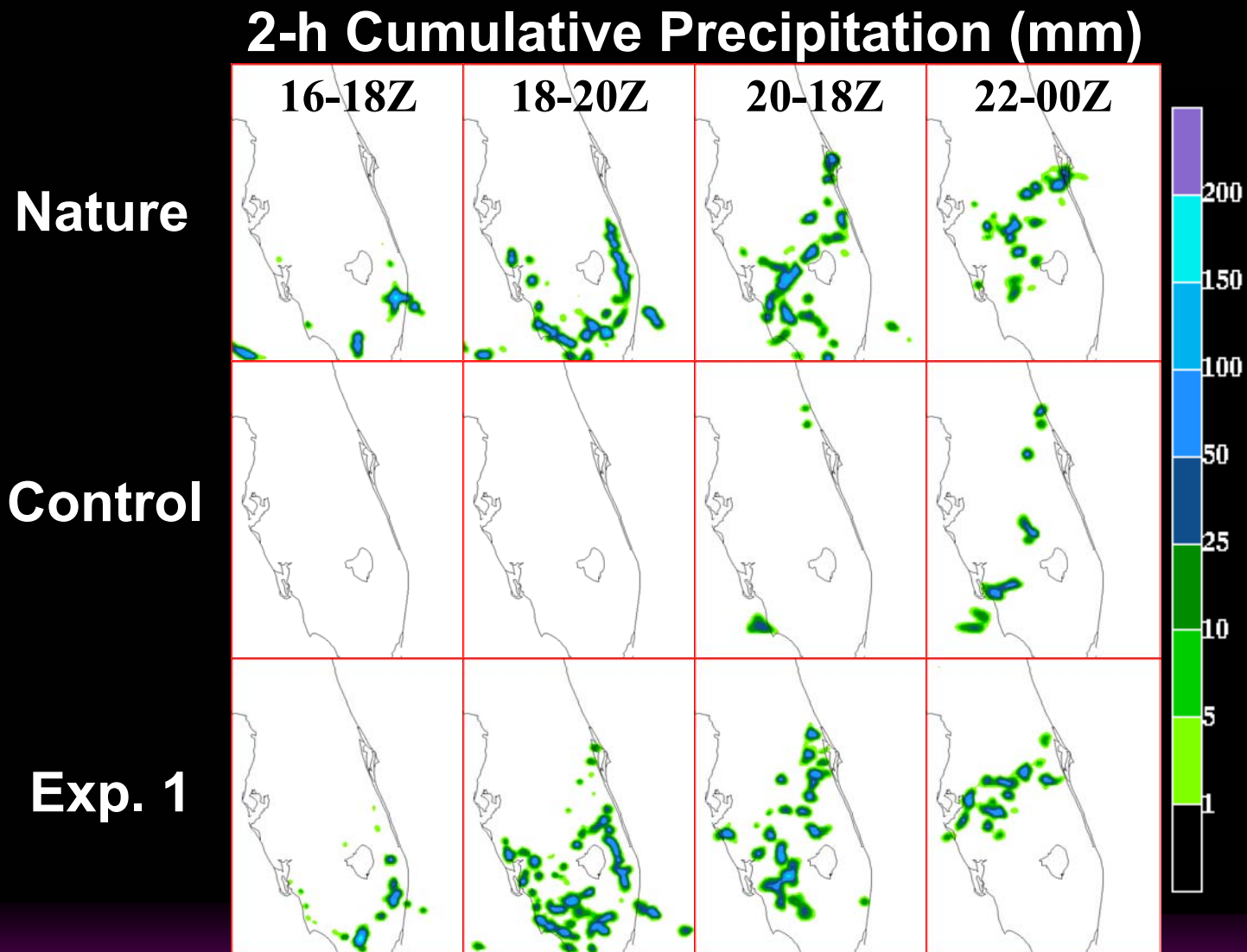
# Probe Deployment Statistics



Probe Distribution by Time & Altitude
Deployment Domain

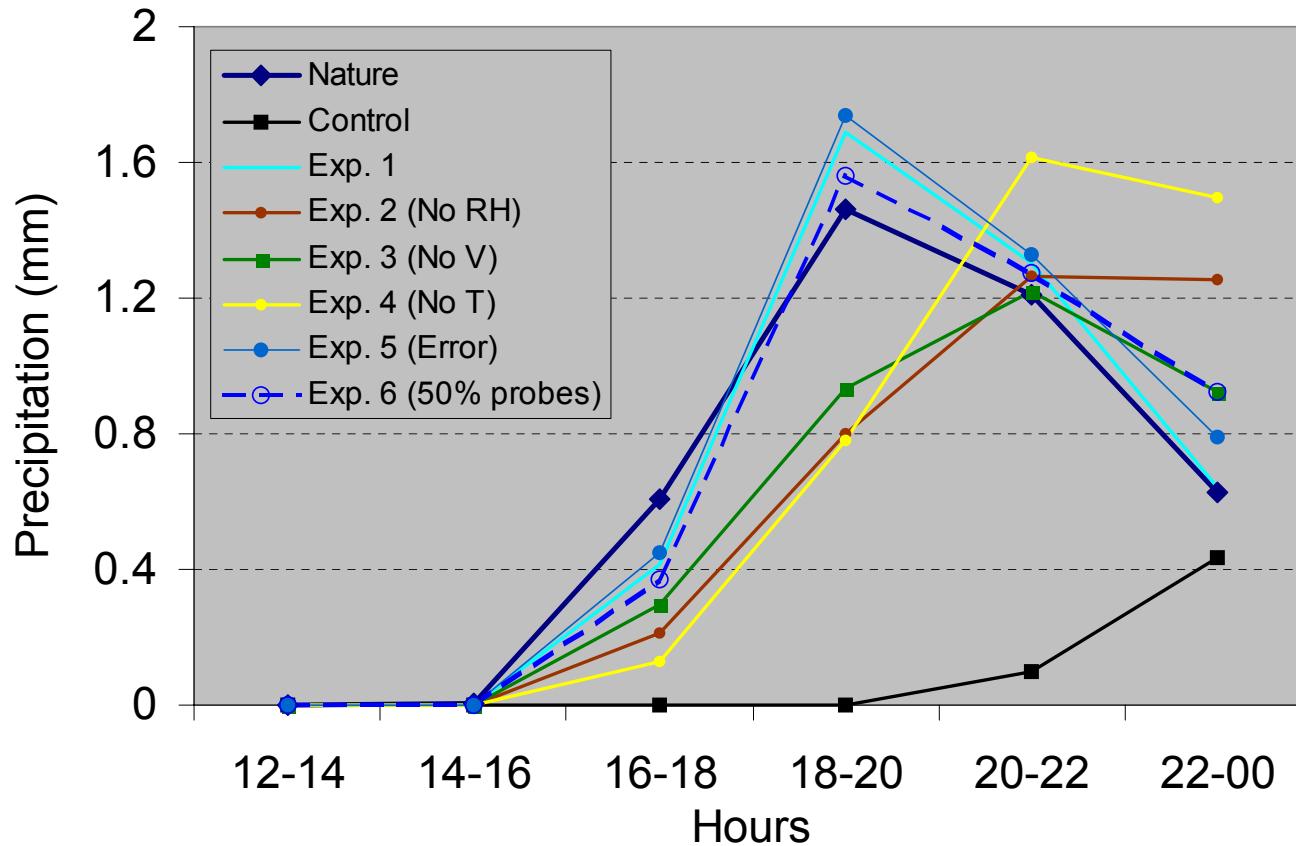

Probe Distribution by Time & Altitude
Assimilation Domain

# Simulation Results
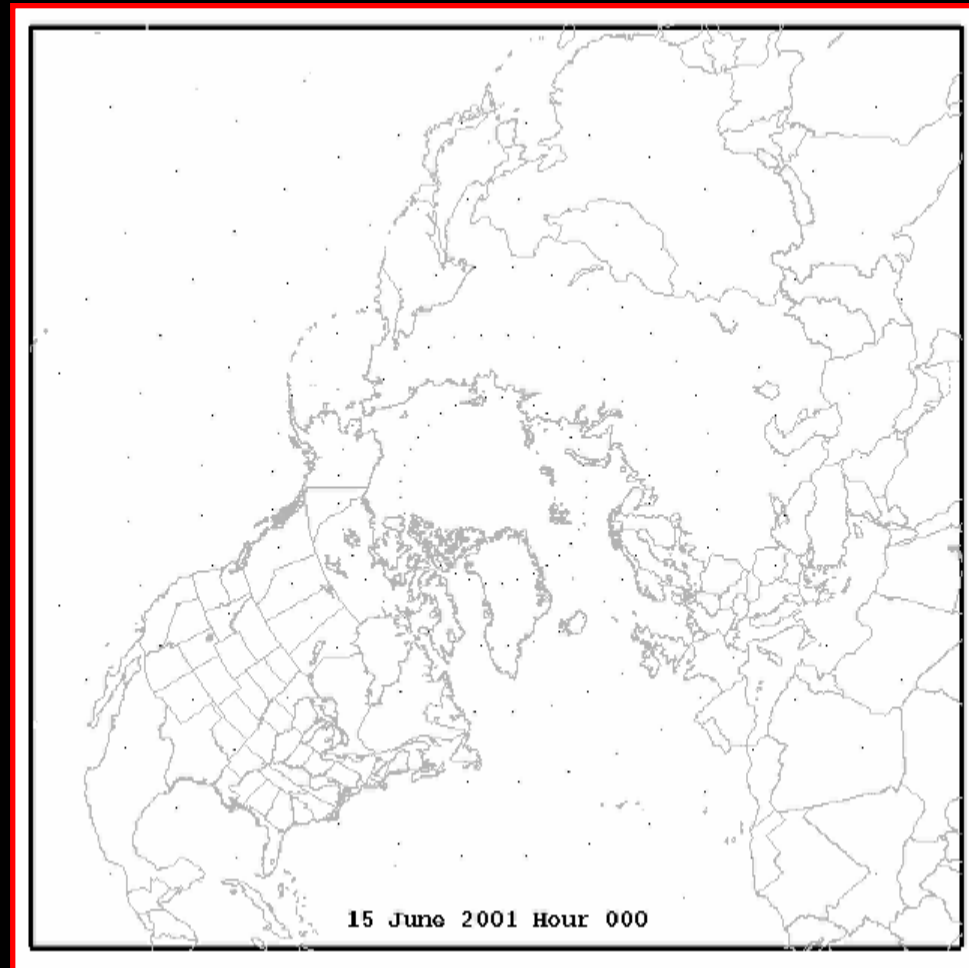


2-h Cumulative Precipitation (mm)

# OSSE Statistics



Grid-Averaged 2-hour Precipitation

# Hemispheric Simulation

- Simulated release from stratospheric balloons every $10^\circ$ lat x $10^\circ$ lon

- Deployment: 1 probe every 6 min for 4 days (18-km altitude)

- Terminal velocity: 0.01 m s$^{-1}$

- Simulation: 10.5 days (15-25 June 2001)

- Total # of probes ~ 200,000



15 June 2001 Hour 000

- ● > 15 km
- ● 12.5–15 km
- ● 10–12.5 km
- ● 7.5–10 km
- ● 5–7.5 km
- ● 2.5–5 km
- ● < 2.5 km

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Innovation Starts Here

# Phase II Plan

- Study major feasibility issues
  - Explore multi-dimensional parameter space
    - MEMS & meteorological disciplines
    - System design & trade-offs
    - Experimentation as appropriate / practical
  - Develop detailed cost-benefit analysis
    - Projected per unit & deployment cost
    - Comparisons with future observing systems
  - Continue extensive use of simulation
    - Expand / enhance OSSEs to study data impact
    - Study probe deployment, dispersion scenarios
- Develop technology roadmap & identify enabling technologies
- Continue building advocacy for sponsorship after Phase II

# Summary

- Advanced concept description
  - Mobile network of wireless, micron-scale airborne probes
- Define major feasibility issues
  - Multi-dimensional parameter space
    - MEMS / Engineering
    - Meteorology
- Phase I results & Phase II plans

# Acknowledgments

- NASA Institute for Advanced Concepts
    - Phase I funding
- NASA Kennedy Space Center Weather Office
    - Dr. Francis Merceret – Chief, Applied Meteorology Unit
    - Access to 32-processor LINUX cluster used for ARPS simulations
- Center for Analysis and Prediction of Storms – University of Oklahoma

manobianco.john@ensco.com