An Overview of Agency Highlights, Research Accomplishments at NASA Ames with Emphasis on High End Computing Research and Quantum Computing

Dr. Eugene Tu
Director, NASA Ames Research Center
Your Planet is Changing

- Measuring Water Use
- Simulating Worldwide Weather (GEOS-5)
- Measuring Ice Thickness
- Seeing Thru the Clouds
- Understanding Global Warming
- Air Pollution Reduction
- Jason-3 sees Ongoing El Niño
- OCO-2
- Suomi NPP
- OSTM/Jason-2
- CALIPSO
- CloudSat
- Aura
- GPM
- Landsat 8 (USGS)
- Landsat 7 (USGS)
- RapidSCAT (ISS)
- SMAP
- DSCOVR (NOAA)
- ECO-1
Off the Earth, for the Earth

- Dragon Cargo (SpaceX)
- Cygnus (Orbital)
- Crew Dragon (SpaceX)
- Falcon 9 (SpaceX)
- CST-100 STARLINER (Boeing)
- Atlas V (Boeing)
- Antares (Orbital)
- Falcon 9 (SpaceX)

[Logos and images of space missions]
Technology Drives Exploration

Space Travel
Manufacturing, Materials, 3-D Printing
Living in Space
Science Instruments
High-Tech Computing
Robotics
NASA Is With You When You Fly

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Vehicles
- Transition to Alternative Propulsion and Energy
- Real-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation
NASA: We’re Out There

Hubble Space Telescope

James Web Space Telescope

K2: Kepler’s Second Light

Icy Worlds: Habitability and Life Detection

Origin and Nature of Life, Co-evolution with Planet Earth

Mars: Habitability of Early Mars

TESS

SOFIA

NASA: We’re Out There

Icy Worlds: Habitability and Life Detection

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TESS

SOFIA
60 Years of Mars Exploration

Illustration by:
Bryan Christie Design
Updated: 2015

- Soviet Union
- United States
- Russia
- Japan
- ESA
- India

1960
2020
2018 Insight Lander
2011 Curiosity Rover
2007 Phoenix Scout
2020 EXOMARS Rover (ESA)
Distance:
- 62 mi
- 180-300 mi
- 240,000 mi
- 36 million mi

Mission Duration:
- 6 Months
- 12 Months
- 3 Years

Spaces:
- ISS Studies & free flyers in LEO
- Ground Studies
- Moon
- Near Earth Objects
- Mars

Unknown spaces
Ames is One of the Early NACA Laboratories

Joseph S. Ames
NASA Centers and Installations

- Ames Research Center
- Jet Propulsion Laboratory
- Armstrong Flight Research Center
- Glenn Research Center
- Johnson Space Center
- Stennis Space Center
- Kennedy Space Center
- Marshall Space Flight Center
- Goddard Space Flight Center
- Langley Research Center
- Headquarters
Ames Research Center

- Occupants:
  - ~1130 civil servants; ~2,100 contractors; 1,650 tenants
  - 855 summer students in 2016

- FY2016 Budget: ~$915M (including reimbursable/EUL)

- ~1,900 acres (400 acres security perimeter); 5M building ft²

- Airfield: ~9,000 and 8,000 ft runways
Core Competencies at Ames Today

- Air Traffic Management
- Entry Systems
- Advanced Computing & IT Systems
- Intelligent/Adaptive Systems
- Cost-Effective Space Missions
- Aerosciences
- Astrobiology and Life Science
- Space and Earth Sciences
Air Traffic Management

FIM - Flight Deck Interval Management for Arrival Operations

CMS - Controller-Managed Spacing in Terminal Airspace

TMA-TM - Traffic Management Advisor with Terminal Metering

UAS Traffic Management

Air Traffic Demonstration – ATD-1
Intelligent Adaptive Systems

**Activity Mission Planning For Mars**

**Planning And Scheduling For Human Robotic Teams / Future**

**Astronauts Self-scheduling And Planning**

**Payload & Drill Subsystem**

**Planetary Lake Lander**
Adaptive science for dynamic phenomena in deep-space missions. Field testing in Chile.

**Self Driving Car**
Adapt space robotics technology to “fleet management” use.

**Astrobee Free-Flyer**
Autonomous nav, docking and recharge, and mobile sensor IVA work on the ISS.
Cost-Effective Space Missions @ Ames

Biosentinel

TechEdSat-4

TechEdSat-5

LCROSS (2009)

LADEE (2013)

PhoneSat (2013), EDSN (2013)
Astrobiology and Life Sciences

Advanced Life Support Technologies

- Dry Electrode ECG System
- Rodent Research-1 (SpaceX-4)
- Experimental cassette for Seedling Growth-2
- Water Recovery
- Air Revitalization
- Waste Recovery
- Synthetic Biology
- Regenerable water processing membrane

Solar System and Beyond:
Our Journey of Discovery
Exoplanet Biosignatures

Icy Worlds:
Habitability and Life Detection

Mars: Habitability of Early Mars

Origin and Nature of Life, Co-evolution with Planet Earth

Technology: Technology Drives Exploration
Global Partnerships Employing Collaborative Technologies

NASA Astrobiology Institute
LIFE IN THE UNIVERSE
Space and Earth Sciences

Understanding Mars Climate

With Clouds

Global Circulation Model

Without Clouds

Field Studies in Antarctica

REMS

2007: CheMin installed in MSL

In Support of Curiosity

ChemCam

SAM

SOFIA

Kepler

Understanding Mars Climate

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Kepler
Advanced IT and Computing Systems

Supercomputing Systems

Big Data Analytics

Large Scale Visualization

Enterprise Managed Cloud Computing

Disruptive Technologies

Quantum Computing

NEX
Modeling and Simulation
Advanced IT and Computing Systems

Capacity Computing

Time Critical Computing

Capability Computing

KEPLER
Need for Advanced Computing

Enables modeling, simulation, analysis, and decision-making

- Digital experiments and physical experiments are tradable
- Physical systems and live tests generally expensive & dangerous (e.g., extreme environments), require long wait times, and offer limited sensor data
- NASA collects and curates vast amounts of observational science data that require extensive analysis and innovative analytics to advance our understanding

- Decades of exponentially advancing computing technology has enabled dramatic improvements in cost, speed, and accuracy – in addition to providing a predictive capability
- Many problems pose extremely difficult combinatorial optimization challenges that can only be solved accurately using advanced technologies such as quantum computing
- NASA’s goals in aeronautics, Earth & space sciences, and human & robotic exploration require orders-of-magnitude increase in computing capability to enhance accuracy, reduce cost, mitigate risk, accelerate R&D, and heighten societal impact
Advanced Computing Environment

Quantum Computing

Neuromorphic Computing

SUPERCOMPUTING

Collaborative Environments

Machine Learning

Cloud Computing
NASA’s Diverse HPC Requirements

- Engineering requires HPC resources that can process large ensembles of moderate-scale computations to efficiently explore design space (*high throughput / capacity*)
- Research requires HPC resources that can handle high-fidelity long-running large-scale computations to advance theoretical understanding (*leadership / capability*)
- Time-sensitive mission-critical applications require HPC resources on demand (*high availability / maintain readiness*)
Balanced HPC Environment

Computing Systems

- **Pleiades**: 246K-core SGI Altix ICE (now HPE) with 4 generations of Intel Xeon (64 nodes GPU-enhanced: Nvidia M2090, K40; 32 nodes have Phi 5110P); 938 TB RAM; 7.25 PF peak (#15 on TOP500, #10 on HPCG)
- **Electra**: 32K-core Altix ICE with Intel Broadwell; modular container; 147 TB RAM; 1.24 PF peak
- **Merope**: 22K-core Altix ICE with Intel Westmere; 86 TB RAM; 252 TF peak
- **Endeavour**: Two SGI UV2000 nodes with 2 and 4 TB shared memory SSI via NUMALink-6; 32 TF peak
- **hyperwall**: 2560-core Intel Ivy Bridge, 128-node Nvidia GeForce GTX78 cluster for large-scale rendering & concurrent visualization (240M pixels)

Data Storage

- 49 PB of RAID over 7 Lustre filesystems
- 490 PB of tape archive

Networks

- InfiniBand interconnect for Pleiades in partial hypercube topology; connects all other HPC components as well
- 10 Gb/s external peering
Modular Supercomputing Facility (MSF)

Current HEC Facility
- Limited to 6 MW electrical power of which 25% used for cooling
- Open-air cooling tower with four 450 T chillers

Prototype MSF (FY17)
- Modular container currently holds Electra (16 Broadwell-based racks)
- External air fan cooling; switch to adiabatic evaporative cooling when needed
- PUE of 1.03 resulting in 93% power savings and 99.4% water use reduction over our traditional computer floor
- Pad has 2.5 MW of electrical power and can accommodate 2 modules
- In production use since Jan ‘17
- Second module being added with 4 E-Cells, bringing Electra to 4.78 PF peak

Full MSF (FY18 – FY22)
- Larger second pad with 30 MW electrical power and associated switchgear
- Ability to hold up to 16 modular units (and 1 M cores)
- Flexibility to rapidly modify and react to changes in NASA requirements, computing technology, and facility innovations
Scientists and engineers plan computational analyses, selecting the best-suited codes to address NASA's complex mission challenges.

Performance Optimization

NAS software experts utilize tools to parallelize and optimize codes, dramatically increasing simulation performance while decreasing turn-around time.

Data Analysis and Visualization

NAS visualization experts apply advanced data analysis and rendering techniques to help users explore and understand large, complex computational results.

Computational Modeling, Simulation, and Analysis

NAS support staff help users productively utilize HPC resources (hardware, software, networks, and storage) to meet NASA's needs.

Outcome: Dramatically enhanced understanding and insight, accelerated science and engineering, and increased mission safety and performance.
Helicopter Rotor Aerodynamics & Aeroacoustics
Time-Evolving Global State of Ocean
Launch Environment
Low Density Supersonic Decelerator
NASA Earth Exchange (NEX)

A virtual collaborative environment that brings scientists and researchers together in a knowledge-based social network along with observational data, necessary tools, and computing power to provide transparency and accelerate innovation: **Science-as-a-Service**

**VIRTUAL COLLABORATION**
Over 650 members

**CENTRALIZED DATA REPOSITORY**
Over 3.5 PB of observational data

**SCALABLE COMPUTING**
Heterogeneous and remote, scalable computing

**KNOWLEDGE**
Workflows, virtual machine images
High-resolution projections for climate impact studies

Global vegetation biomass at 100m resolution by blending data from 4 different satellites

High-resolution monthly global data for monitoring crops, forests, and water resources

Sample publication using NEX environment: 

Machine learning and data mining – moving toward data-driven approaches
Quantum Computing 101

- Quantum mechanics deals with physical phenomena at very small scales (~100nm) and at very low temperatures (few K) where actions are quantized.
- The outcome of a quantum experiment is probabilistically associated both with what was done before the measurement and how the measurement was conducted.
- Qubits (quantum bits) can exist in a superposition of states, allowing $n$ qubits to represent $2^n$ states simultaneously.
- At the end of a computation, on measurement, the system collapses to a classical state and returns only one bit string as a possible solution.

Numerous Implementations

- Ion trap with microwave control
- Penning trap in optical lattice
- Photonic Quantum
- Photonic with optical waveguides
- University of Bristol
- Quantum dots
- RWTH
- Trapped Ions and Neutral Atoms
- Nanoelectronics, NMR, Diamond Chips,
- Photonic Quantum Chips
- NIST
- Nanoelectronics, NMR, Diamond Chips,
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Quantum Computing for NASA Applications

**Objective:** Find “better” solution
- Faster
- More precise
- Not found by classical algorithm

**Common Feature:** Intractable (NP-hard / NP-complete) problems!
Quantum Annealing

A physical technique to solve combinatorial optimization problems

\[ E(z_1, z_2, \ldots, z_n) = \left(1 - \frac{t}{T}\right) H_0 (\{z\}) + \frac{t}{T} H_P (\{z\}) \]

• N-bit string of unknown variables \( \{z\} \)
• \( H_0 \): Hamiltonian with known ground state
• \( H_P \): Hamiltonian whose ground state represents solution to the problem
• Large \( A(t) \) responsible for quantum fluctuations slowly (adiabatically) lowered to zero while maintaining minimum energy of the system at all times
• In conjunction, cost function of interest \( B(t) \) gradually turned on
• Transitions between states occur via tunneling through barriers due to quantum fluctuations
• Solution is configuration \( \{z\} \) that produces minimum \( E \) with non-zero probability
• Method similar to simulated annealing where transitions between states occur via jumping over barriers due to thermal fluctuations
D-Wave System Hardware

• Collaboration with Google and USRA via Space Act Agreement led to installation of system at NASA Ames in early 2013
• Started with 512-qubit Vesuvius processor – currently 2031-bit Whistler
• 10 kg of metal in vacuum at ~15 mK
• Magnetic shielding to 1 nanoTesla
• Protected from transient vibrations
• Single annealing typically 20 µs
• Typical run of 10K anneals (incl. reset & readout takes ~4 sec)
• Uses 15 kW of electrical power

Focus on solving discrete optimization problems using quantum annealing
Programming the D-Wave System

1. **Map the target combinatorial optimization problem into QUBO**
   
   No general algorithms but smart mathematical tricks (penalty functions, locality reduction, etc.)

   \[
   \alpha_{ijk} z_i z_j z_k \\
   \alpha_{ik} y_i z_k + \\
   \beta_{ik} (3y_i - 2z_i y_j - 2z_j y_i + z_i z_j) \\
   \sum_{ij} Q_{ij} z_i z_j \rightarrow \\
   \sum_i h_i s_i + \sum_{i,j} J_{ij} s_i s_j
   \]

   **Mapping not needed for random spin-glass models**

2. **Embed the QUBO coupling matrix in the hardware graph of interacting qubits**

   D-Wave qubit hardware connectivity is a Chimera graph, so embedding methods mostly based on heuristics

   \[
   Q_{ij} =
   \]

   **Embedding not needed for native Chimera problems**

3. **Run the problem several times and collect statistics**

   Use symmetries, permutations, and error correction to eliminate the systemic hardware errors and check the solutions

   **Performance can be improved dramatically with smart pre-/post-processing**
Current NASA Research in Quantum

Complex Planning and Scheduling

Calibration of Quantum Annealers

Effect of Noise on Quantum

Optimal Embedding and Parameter Setting

Graph Isomorphism

Graph-based Fault Detection

Circuit Breakers

Sensors

Observations

Number of qubits

Number of qubits

$h_{\text{prog}} = h_{\text{spec}} + h_{\text{bias}}$

$h$ biases (before) correction

$h$ biases after correction

Biswa, SMC-IT, 28 Sept 2017
Advanced Computing Mission

Enable the science & engineering required to meet NASA’s missions and goals

Effective, stable, production-level HPC environment

Advanced technologies to meet future goals
Major Research Facilities

- Wind Tunnels
- ARC Jet Complex
- Range Complex
- Simulators
- Advanced Supercomputing
Partnerships at Ames

Commercial

Virtual Institutes

NASA Research Park

Inter-Agency

International

NASA Ames Campus

Shenandoah Historic District

NRP South Campus

Bay View

Eastside/ Airfield

Carnegie Mellon University
Silicon Valley

Bloomenergy

Made in Space

skyTran

Virtual Institutes

Academia

NASA Astrobiology Institute

NARI NASA AERONAUTICS RESEARCH INSTITUTE

S3VI

SERVI