SNAP
Small Next-generation Atmospheric Probe

A Multiprobe Flagship Mission to Explore Ice Giant Uranus
March 18, 2018

Kunio Sayanagi, Principal Investigator
Hampton University
Robert A. Dillman, Chief Engineer
NASA Langley Research Center
## Study Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kunio M. Sayanagi (PI)</td>
<td>Hampton University</td>
</tr>
<tr>
<td>Robert A. Dillman</td>
<td>NASA Langley Research Center</td>
</tr>
<tr>
<td>David H. Atkinson</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>Amy A. Simon</td>
<td>NASA Goddard Space Flight Center</td>
</tr>
<tr>
<td>Michael H. Wong</td>
<td>University of California, Berkeley</td>
</tr>
<tr>
<td>Thomas R. Spilker</td>
<td>Independent Consultant</td>
</tr>
<tr>
<td>Sarag Saikia</td>
<td>Purdue University</td>
</tr>
<tr>
<td>Jing Li</td>
<td>NASA Ames Research Center</td>
</tr>
<tr>
<td>Drew Hope</td>
<td>NASA Langley Research Center</td>
</tr>
<tr>
<td>W. Chris Edwards</td>
<td>NASA Langley Research Center</td>
</tr>
</tbody>
</table>

### Mission Design Center:

**NASA Langley Research Center Engineering Design Studio**
Mission Science Objectives

Tier-1 Objectives:
*Determine spatial variability in atmospheric properties:*
- Vertical distribution of cloud-forming molecules
- Thermal stratification and static stability
- Atmospheric dynamics as a function of depth

Tier-2 Objectives (Tech Search only in this study):
*Determine Bulk Composition:*
- Measure abundances of the noble gases (He, Ne, Ar)
- Measure isotopic ratios of H, C, N, and S
Science Instruments

**NanoChem Atmospheric Composition Sensor:**
Vertical distribution of cloud-forming molecules

**Atmospheric Structure Instrument (ASI):**
Thermal stratification and static stability

**Ultra-Stable Oscillator (USO):**
Atmospheric dynamics as a function of depth (Through Doppler Wind Experiment)
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Mass</th>
<th>Power</th>
<th>SNAP Data Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>NanoChem</td>
<td>Atmospheric Composition</td>
<td>1.0 kg</td>
<td>0.1 W</td>
<td>1.08 Mbit</td>
</tr>
<tr>
<td>ATMOSPHERIC STRUCTURE INSTRUMENT</td>
<td>Pressure Temperature Acceleration</td>
<td>1.3 kg</td>
<td>5.7 W</td>
<td>6.25 Mbit</td>
</tr>
<tr>
<td>Ultra-Stable Oscillator</td>
<td>Doppler Wind Experiment</td>
<td>1.7 kg</td>
<td>3.2 W</td>
<td>0.05 Mbit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Housekeeping Only)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4 kg</td>
<td>9 W</td>
<td>7.35 Mbit</td>
</tr>
</tbody>
</table>
NanoChem: How it works

- Measures Changes in Resistivity in response to gas composition
- Sensor Heads can be arrayed up to 16 x16 grid on a single chip
- Under Development at NASA Ames (PI: Jing Li)

NanoChem Advantages:
- Small Sensor Package
- Low Mass, Lowe Power
- Can operate without Vacuum Pump

NanoChem response to ammonia

Gas molecules

NanoChem: How it works

Gas off

Gas on

NanoChem response to ammonia
Launched and Operated in Space
Navy MidSTAR-1 satellite in 2007

Environmental Monitoring on ISS

Sensitivity demonstrated for:
... CH₄, H₂O, and NH₃, among others
... in Mars and Earth conditions

Need to develop sensitivities for:
... H₂S
... in Giant Planet Conditions

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Sensitivity/Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>1 ppm in air</td>
</tr>
<tr>
<td>Hydrazine</td>
<td>10 ppb tested</td>
</tr>
<tr>
<td>NO₂</td>
<td>4.6 ppb in air</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.5 ppm in air</td>
</tr>
<tr>
<td>SO₂</td>
<td>25 ppm in air</td>
</tr>
<tr>
<td>HCl</td>
<td>5 ppm in air</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>10 ppb in air</td>
</tr>
<tr>
<td>Acetone</td>
<td>10 ppm in air</td>
</tr>
<tr>
<td>Benzene</td>
<td>20 ppm in air</td>
</tr>
<tr>
<td>Cl₂</td>
<td>0.5 ppm in N₂</td>
</tr>
<tr>
<td>HCN</td>
<td>10 ppm in N₂</td>
</tr>
<tr>
<td>Malathion</td>
<td>Open bottle in air</td>
</tr>
<tr>
<td>Diazinon</td>
<td>Open bottle in air</td>
</tr>
<tr>
<td>Toluene</td>
<td>1 ppm in air</td>
</tr>
<tr>
<td>Nitrotoluene</td>
<td>256 ppb in N₂</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>3.7 ppm in air</td>
</tr>
</tbody>
</table>
NanoChem Commercialization

- Development at NASA Ames
  PI: Jing Li
- A/D on NanoChem Attachment
- Power from Phone (~mW)
- Processing on the Phone
- High sensitivity – ppb to ppm
- Data Transmission through Cellular Network
Mission Design Assumptions

1. Baseline Carrier Mission: **Uranus Orbiter with Probe**
   Mission Architecture #5 by Ice Giants Flagship SDT:
   - 1913 kg Uranus Orbiter
   - All-chemical Propulsion (no SEP)
   - 50 kg Science Payload on Orbiter
   - 321 kg Probe (= Primary Probe = PP)

2. Add SNAP as a **Second Probe**

3. Deliver PP and SNAP at Uranus with large spatial separation

4. PP/SNAP and CRSC trajectories must enable data relay
SNAP Study Goals

Enable Future Multi-Probe Planetary Missions:

– Advocated by past Decadal Surveys
– Provide data on spatially varying atmospheric phenomena.
– **2003 Survey**: Advocated for a Jupiter Multi-Probe mission
– **2013 Survey**: Emphasized that a second probe can significantly enhance the scientific value of a probe mission
– Never realized due to perceived high-cost.
– SNAP Design applicable to Saturn, Uranus and Neptune (with possibilities for Venus)

**SNAP Enables Future Multi-Probe Missions**
Baseline Carrier Mission

Earth-VEEJ-Uranus (Modified NASA Ice Giants SDT Architecture #5)

- Launch: 5/25/31, VEEJ gravity-assists + Two DSMs
- Launch Vehicle: Atlas V541, 
  \( \sim 4450 \text{ kg} \ C_3 = 11.9 \text{ km}^2/\text{s}^2 \)
- 12-year cruise to UOI

Uranus Arrival: May 17, 2043

- Close to 2049 Equinox
- After 2028 Northern Summer Solstice
- Voyager flyby 1986 was during Southern Summer Solstice
- Periapsis \( r_p = 1.05 \text{ } R_U \)
- Capture orbit period = \( \sim 142 \text{ days} \)
Impact on Carrier Mission

Trajectory:
- Release SNAP after Uranus Orbit Insertion

Hardware:
- Mounting & deployment hardware
- Pre-deployment power & data connections
- Orbiter propellant

Software & operations:
- Accommodate second probe delivery and data relay
Add SNAP as a Second Probe

From Ice Giant SDT Study

SNAP

Not to scale with Orbiter

Orbiter (CRSC)
- Mass in orbit: 1913 kg
- Payload Mass: 50 kg
- UOI $r_p$: 1.05 $R_U$
- Orbital Period: ~142 days

Primary Atm. Probe (PP)
- Mass: 321 kg
- Diameter: 1.2 m, 45° sphere-cone
- 10-bar* pressure altitude
- Probe release: ~60 days
- EPFA: -20° to -50°

SNAP
- Mass: 30 kg
- Diameter: 0.5 m, 45° sphere-cone
- 10-bar* pressure altitude
- Probe release: 30–60 days
- EPFA: -20° to -50°

Baseline Orbiter and Probe: Ice Giant SDT Architecture #5

*10-bar is requirement for hardware operation for margin, science objective is to reach 5-bar.
Interplanetary Trajectory Options

- A broad of catalog of ballistic chemical gravity-assist trajectory options
- SEP options not investigated due to high mass

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Launch Vehicle</th>
<th>Flyby Sequence</th>
<th>Launch C₃ (km²/s²)</th>
<th>Interplanetary Cruise (yrs)</th>
<th>DSM (m/s)</th>
<th>Arrival Mass (kg)</th>
<th>UOI ΔV (m/s)</th>
<th>Mass in Orbit (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/25/2031</td>
<td>Atlas V 541</td>
<td>Earth-VEEJ-Uranus</td>
<td>11.9</td>
<td>12</td>
<td>565</td>
<td>3582.5</td>
<td>1680</td>
<td>1850</td>
</tr>
<tr>
<td>7/18/2031</td>
<td>Delta IV Heavy</td>
<td>Earth-VEJ-Uranus</td>
<td>20.3</td>
<td>10.9</td>
<td>737</td>
<td>5265</td>
<td>2240</td>
<td>2393</td>
</tr>
<tr>
<td>4/6/2031</td>
<td>Delta IV Heavy</td>
<td>Earth-VVE-Uranus</td>
<td>25.5</td>
<td>11.5</td>
<td>1063</td>
<td>4751</td>
<td>1580</td>
<td>1885</td>
</tr>
</tbody>
</table>

Dual probe delivery architecture possible for multiple interplanetary trajectory options
Challenges of Multi-Probe Missions

- Deliver PP and SNAP at two significantly different locations (latitude, longitude, time-of-day)

- During each probe’s atmospheric descent:
  - CRSC used to receive data from probe, relay to Earth
  - CRSC must be within 30 degree comm. cone around zenith.
  - Each probe must reach at >5-bar while CRSC is in 30-deg cone.
Accessibility of Entry Locations

- Trajectory gives access to a wide range of latitudes and spatial distribution for the entry probes

- One probe can enter the night side and the other on the day side (After 2028 Northern Summer Solstice)

Red: Crosses rings
Yellow: Exceeds 200g during entry
Green: Feasible
Dual-Probe Delivery Trajectories

Trajectory Solution to add SNAP to Ice Giant SDT Architecture #5
Con-Ops: Dual Probe Delivery
Overall Mission ConOps

- Overall mission ConOps with critical events
- \( T = 0 \) day is UOI

PROBE TIMELINES

- \( T - 67d \)
- \( T - 60d \)
- \( T - 55d \)
- \( T - 1h \)
- \( T = 0d \)
- \( T \approx 0d \)
- \( T + 71d \)
- \( T + 73d \)
- \( T + 116d \)
- \( T + 121d \)
- \( T + 146d \)

MANEUVERS & OPERATIONS

- PTM-PAP
- SNAP: Small Next-generation Atmospheric Probe
- PTM: Probe Targeting Maneuver
- ODPTM: Orbiter Divert and Periapsis Targeting Maneuver
- UOI: Uranus Orbit Insertion
- ACM: Apoapsis Correction Maneuver

Not to Scale
Atmospheric Entry & Descent

Separation Chute Diameter = 1.5 m

Descent Chute Diameter = 0.1 m Stabilizer

Release Backshell using Separation Chute
Pull out Descent Chute
T = 175 s

Descent Phase
Reach 5 bar at T = 1,870 s (31 min)
Reach 7.3 bar at T = 2,400 s (40 min)

Atmospheric Interface T = 0 s
Peak Heating T = 98 s
& Deceleration T = 101 s

Mortar-deployed Separation Chute
T = 165 s

Separation Chute Opens,
Release Foreshell T = 170 s
Atmospheric Entry & Descent

Pressure Level [bar]

5-bar Threshold Mission Target

Altitude Above 1-bar [km]

40-min Communication Cutoff

0 5 10 15 20 25 30 35 40 45 50

0 1 2 3 4 5 6 7 8 9 10

0 5 10 15 20 25 30 35 40 45 50

-200 -100 0 100 200 300 400 500 600 700 800 900 1000 1100

0 5 10 15 20 25 30 35 40 45 50

0 5 10 15 20 25 30 35 40 45 50

-200 -100 0 100 200 300 400 500 600 700 800 900 1000 1100

Time [min]

Time [min]
Entry & Descent Analysis

**Heating Rate [W/cm²]**

**Dynamic Pressure [kPa]**

**Acceleration [g]**

**Air Speed [Mach]**
Link Analysis takes account of:
- Atmospheric Radio Absorption (NH₃ + CH₄)
- Attenuation through Link Range
- Transmitter/Receiver Antenna Gain
- Link Geometry
- Receiver Noise Model

2.2 GHz (S-Band)

Data Generation

3500 bps Data Rate Worst-case
Baseline SNAP Design Summary

- 0.5 m diameter, 30-kg, 45° sphere-cone heat shield
- SNAP is released ~30 days before entry (from ~142-day orbiter orbit)
- After PP, SNAP enters prograde with EFPA between -40° and -45° and V = 22.4 km/s
- SNAP enters on the day side of Uranus
- Orbiter-SNAP separation 36000–13000 km during mission (~40-mins contact time)
  - Short distance range enables sufficient data rate
- Deceleration and aerothermal conditions all well within design limits
- Fore-body TPS = HEEET; Aft-body TPS = PICA

### Entry Conditions of SNAP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Heat Rate, W/cm²</td>
<td>3250–3750</td>
</tr>
<tr>
<td>Stagnation Pressure, bar</td>
<td>2.75–3.75</td>
</tr>
<tr>
<td>Heat Load, J/cm²</td>
<td>29227–34515</td>
</tr>
<tr>
<td>Peak Inertial Load, Earth G’s</td>
<td>196–270</td>
</tr>
</tbody>
</table>
Baseline Hardware Configuration

- Descent Chute
- Antenna
- Avionics
- TPS (PICA)
- TPS (HEEET)
- Transmitter
- NanoChem
- Radio-Isotope Heater Unit
- Separation Chute
- Chute Mortar
- ASI (Accelerometer)
- Clock
- ASI (Temperature)
- ASI (Pressure)
- ASI Inlet Mast
- Batteries
- USO
### Probe Mass Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Subtotal Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreshell TPS (HEEET) + Structure</td>
<td>5.74</td>
<td></td>
</tr>
<tr>
<td>Aftshell TPS (PICA) + Structure + Separation Mechanism</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td><strong>Aeroshell Total</strong></td>
<td><strong>14.03 kg</strong></td>
<td></td>
</tr>
<tr>
<td>Descent Module Structure</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Parachutes</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Science Instruments</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Engineering Subsystems</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td><strong>Descent Module Total</strong></td>
<td><strong>9.85 kg</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Atmospheric Entry Mass Total</strong></td>
<td><strong>23.88 kg</strong></td>
<td></td>
</tr>
<tr>
<td>Mass Margin (25%)</td>
<td>6.12 kg</td>
<td></td>
</tr>
<tr>
<td><strong>Total Probe Mass</strong></td>
<td><strong>30 kg</strong></td>
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</tbody>
</table>
Probe Power Summary

<table>
<thead>
<tr>
<th>Sub-system/ Instruments</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-Stable Oscillator</td>
<td>3.2 W</td>
</tr>
<tr>
<td>ASI</td>
<td>5.7 W</td>
</tr>
<tr>
<td>Nano-Chem Sensor</td>
<td>0.1 W</td>
</tr>
<tr>
<td>Avionics</td>
<td>4 W</td>
</tr>
<tr>
<td>Radio Transmitter</td>
<td>50 W</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>0.1 W</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>63.1 W</strong></td>
</tr>
</tbody>
</table>

In left, we assume use of x3 RHUs.

Battery-powered heaters are also possible.

After probe release until atmo. entry

→ SNAP needs 3W of heating.

For 30-day “coast”…

- Li-Ion (current, 145 Wh/kg) = 21 kg
- Li-Ion (future, 400 Wh/kg) = 7.5 kg
- Li/CFx (639 Wh/kg) = 4.7kg

<table>
<thead>
<tr>
<th>Phase</th>
<th>Energy Requirement, Wh</th>
<th>Battery Mass, kg</th>
<th>Number of Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNAP Mission</td>
<td>164</td>
<td>0.257</td>
<td>3</td>
</tr>
</tbody>
</table>
Mass Impact on Carrier Mission by Addition of SNAP

- SNAP margined mass = 30 kg.
- Requires additional mass to baseline Uranus mission:
  - Probe Support Systems on the Orbiter
  - Propellant on the Orbiter

<table>
<thead>
<tr>
<th>Systems/ Subsystem</th>
<th>Mass, kg</th>
<th>Margined Mass, kg</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Support Systems Total</td>
<td>4</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Spin ejection device</td>
<td>3</td>
<td>4</td>
<td>30%</td>
</tr>
<tr>
<td>Harness/ umbilicals</td>
<td>1</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>SNAP Mass</td>
<td>23.88</td>
<td>30</td>
<td>25%</td>
</tr>
<tr>
<td>Orbiter SNAP Support Propellant</td>
<td>30</td>
<td>36</td>
<td>30%</td>
</tr>
<tr>
<td><strong>Total Mass Addition to Carrier Mission</strong></td>
<td><strong>58</strong></td>
<td><strong>72.3</strong></td>
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</tbody>
</table>
Cost Analysis

SNAP Cost and Schedule By Year

2031 Launch
2042 Arrival

Est. SNAP Cost = 74.8M (FY18$)
IGSDT Arch. #5 Cost = 2B (FY15)

$75M = 4% Δcost to enable a multi-probe mission
Technology Needs

- Instrument/Sensor Technology
  NanoChem is TRL = 4 today (Under Dev. at Ames)

- Thermal Protection System:
  HEEET is needed for low density (Under Dev. at Ames)

- Power - Batteries:
  Low-temp., High Specific Energy Batteries alleviate need for RHUs

- Electronics:
  Low-survival temp will reduces heater power needs
Study Components

Add SNAP as a Second Probe to a Future Uranus Orbiter with Probe mission

- Science Objectives*
- Top-Level Design Assumption (Pick Baseline Mission)*
- Interplanetary Trajectories*
- Dual-Probe delivery options*
- Atmospheric Characterization*
- Atmospheric Entry and Descent Analysis*
- Con-Ops*
- Link Analysis*
- Instrument Technologies*
- Mechanical Design*
- Thermal Analysis
- Power*
- CDH + Electronics
- Risk
- Cost*

* Items Included in this Presentation
SNAP Design Summary

Dual-Probe Trajectory Solutions Found
SNAP Mass: 30 kg (Instrument Mass = 4 kg)
Total Data Return = 7.3 Mbit
Total Mass Addition to Carrier Mission: 72.3 kg
Total Estimated Cost: 74.8M (FY18$)
Enabling Technologies: NanoChem & HEEET
Enhancing Technologies: Better Batteries
SNAP: Enable Future Multi-Probe Missions

Galileo Probe
SNAP Probe
Science Objectives:

**Tier-1 Objectives:** Determine spatial differences of the following atmospheric properties from the Main Probe entry site:
1. Vertical distribution of cloud-forming molecules
2. Thermal stratification
3. Wind speed as a function of depth

**Tier-2 Objectives:** Augment Main Probe Science Objectives:
4. Measure abundances of the noble gases (He, Ne, Ar)
5. Measure isotopic ratios of H, C, N, and S

Mission Overview:

**Baseline Mission Configuration:**
Add SNAP to Uranus Orbiter and Probe Mission
Orbiter delivers Main Probe and SNAP to Uranus

**Baseline Spacecraft Configuration:**
- Mass: 30 kg
- Probe Diameter: 50 cm
- Probe Power: Primary Batteries
- Heatshield Material: HEEET

**Notional Payload:**
- NanoChem: Detect cloud-forming molecules
- Atmospheric Structure Instrument: Measure thermal profile
- Ultrastable Oscillator: Atmospheric Dynamics

Team Members/Institutions

Kunio M. Sayanagi | Hampton University
Robert A. Dillman | NASA Langley Research Center
David H. Atkinson | Jet Propulsion Laboratory
Amy A. Simon | NASA Goddard Space Flight Center
Michael H. Wong | University of California, Berkeley
Thomas R. Spilker | Independent Consultant
Sarag Saikia | Purdue University
Jing Li | NASA Ames Research Center
Drew Hope | NASA Langley Research Center
W. Chris Edwards | NASA Langley Research Center

Supported by: NASA Langley Research Center Engineering Design Studio
BACK UP SLIDES
Engineering Design Studio (EDS), NASA Langley Research Center

- Support PI-led Mission Design & Proposal Development
- Concurrent Engineering Design Capability in Dedicated Room
- Access Strengths of NASA Langley Research Center
  - Atmos. Entry, Descent & Landing
  - Remote-Sensing Measurements
  - Atmospheric In-Situ Measurements
  - Aeronautics
- Proposal Development Support
  - Blue/Red Team Reviews
  - Strength, Weakness, Opportunities, Threats (SWOT) Analysis
  - Mission Cost Analysis
  - Proposal/Project Budget Development
  - Graphics Design
- Dual probe delivery possible for multiple trajectory options
- SNAP mission concept is applicable to many interplanetary trajectories

<table>
<thead>
<tr>
<th>Launch date</th>
<th>Launch Vehicle</th>
<th>Flyby Sequence</th>
<th>Launch $C_3$ (km$^2$/s$^2$)</th>
<th>IP TOF (yrs)</th>
<th>DSM (m/s)</th>
<th>Arrival Mass (kg)</th>
<th>UOI $\Delta V$ (m/s)</th>
<th>Arrival $V_\infty$ (km/s)</th>
<th>Arrival Decl., deg</th>
<th>Mass in Orbit (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/6/2031</td>
<td>Delta IV Heavy</td>
<td>Earth-VVE-Uranus</td>
<td>25.5</td>
<td>11.5</td>
<td>1063</td>
<td>4751</td>
<td>1580</td>
<td>8.04</td>
<td>71</td>
<td>1885</td>
</tr>
</tbody>
</table>
- Shows hyperbolic approach trajectories of orbiter + SNAP (blue, right) and primary probe (red)
- Shows elliptical captured orbit of orbiter (blue, left) and elliptical trajectory of SNAP (green)
- 30° Margined HWHM beam cone is centered around the negative of planet-relative velocity vector of the probes as they undergo entry and descent
- Orange cone: Ongoing probe entry mission but no orbiter-probe contact
- Green cone: When orbiter is in contact with the probe
Baseline Hardware Configuration