JUPITER ICY MOONS ORBITER (JIMO) SCIENCE FORUM

COMPILED OBJECTIVES, INVESTIGATIONS AND MEASUREMENTS

23 JULY 2003

Astrobiology

Objective 1: Detect signs of life on Europa and other icy moons of Jupiter

-- Investigation 1A: Search for the presence of biogenic organics present at the surface and shallow (<1m) subsurface

- *Measurement 1A1*: Determine the mass spectrum of organic molecules from 100 to 100,000 amu down to concentrations of TBD (ideally <1 ng C/l) in order to identify possible biological patterns
- *Measurement 1A2*: Determine concentrations of specific biomarkers known to be relevant to life on Earth. These include lipids, carbohydrates, proteins (including functional domains), nucleic acids and fluorescent co-factors

-- Investigation 1B: Study the isotopic fractionation in organic and inorganic compounds via abiotic and biotic processes

- *Measurement 1B1*: Measure carbon, nitrogen, oxygen, hydrogen, sulfur, iron, manganese isotope ratios in a broad range of organic molecules and inorganic surface residues to search for patterns in isotope distributions that could reflect biological fractionation processes at a precision of 1 per mil.
- *Measurement 1B2*: Measure $^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{18}O$, and H/D ratios in atmospheric compounds such as CO_2, CH_4, H_2O, NH_3, H_2S, etc. (accuracy on the order of 1 to 10 per mil) as potential indicators of metabolic activity.

-- Investigation 1C: Search for presence of potential metabolic byproducts

- *Measurement 1C1*: Measure concentration and spatial distribution of key biogenic gases CH_4, H_2S, NH_3 at partial pressures of 10-4 Pa (ppb at 1 atm) on Europa.

-- Investigation 1D: Determine the distribution and nature of abiotic organic matter on Europa, Ganymede and Callisto for comparison with biogenic organic compounds.

- *Measurement 1D1*: Remote sensing of organics (C-H bonds, near/mid-IR spectroscopy) in surface layers for all icy moons
- *Measurement 1D2*: Direct measurement of concentration and characteristics (molecular weight and structure) in surface deposits on Europa

-- Investigation 1E: Search for organisms by microscopy

- *Measurement 1E1*: Optical and fluorescence microscopic examination of processed (filtered, concentrated) melt water over 0.2 to 1000 μm size range

Objective 2: Determine the habitability of Europa and other icy moons of Jupiter

-- Investigation 2A: Study the composition of surface and shallow subsurface ice

- *Measurement 2A1*: Measure concentrations of major ions (Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, Si^{4+}, alkalinity) and bulk conductivity.
- *Measurement 2A2*: Measure concentrations of biogenic or biologically relevant ions (NO_3^-, NH_4^+, HPO_4^{2-}) and trace elements (Zn, Cu, Mn, Fe, etc.)

- *Measurement 2A3*: Measure pH, eH
- *Measurement 2A4*: Measure concentrations of dissolved, particulate and total organic carbon
- *Measurement 2A5*: Measure isotopic composition of ice, organic matter (C, H, N, O, P, S)

-- Investigation 2B: Determine the environmental resources (energy and nutrients)
- *Measurement 2B1*: Measure concentrations (at nano-molar levels) of electron acceptor/donor pairs such as Fe^{3+}/Fe^{2+}, H_2S /S/SO_2 and oxygen concentrations
- *Measurement 2B2*: Measure volcanogenic concentrations of H_2, CO_2, CH_4, H_2S
- *Measurement 2B3*: Measure thermal and osmotic variations and gradients of important environmental parameters (chemical, density, temperature etc.) in ocean, sediment-ocean interface, ice-water interface, surface, including a compilation of evidence for oceanic circulation patterns.

-- Investigation 2C: Study the effects of the radiation environment on the potential habitability of the surface and near surface environment
- *Measurement 2C1*: Measure the energy and spatial distribution of energetic electrons and ions on the surface of the icy moons
- *Measurement 2C2*: Measure the geochemical modification of inorganic and organic compounds as a function of depth in the surface and near-surface environment

-- Investigation 2D: Geological search for ancient habitats
- *Measurement 2D1*: Image the surface at a resolution of <1m over predetermined critical sites ranging over various relative ages from oldes to youngest

Objective 3: Confirm an ocean on Europa and other icy moons of Jupiter

-- Investigation 3A: Investigate the potential access sites to ocean on Europa, exposing ice-water interface
- *Measurement 3A1*: Determine location of ice-water interface

-- Investigation 3B: Global structure of the ocean-ice layer

-- Investigation 3C: Find any active sites (cracks, etc.)

Remote Sensing: Geomorphology

Objective 1: Determine the origins of surface features and their implications for geological history and evolution

-- Investigation 1A: Evaluation of magmatic processes (intrusion, extrusion, diapirism)

-- Investigation 1B: Evaluation of tectonic processes (isostatic compensation, styles of faulting, flexure and folding)

-- Investigation 1C: Evaluation of impact cratering processes (morphology and distribution)

-- Investigation 1D: Evaluation of gradation (erosion/deposition) processes (impact gardening, sputtering, mass wasting, frosts)

- *Measurement 1ABCD1*: Global topographic mapping (in 2 dimensions, goreless) at better than or equal to 10-m spatial scale, and better than or equal to 1-m relative vertical accuracy (require center of mass control for absolute topography). Spatial scale of absolute control is TBD.

  Justification:
  Europa: Test models of ridge and band formation, chaos formation (e.g., diapiric or melt-through), lithospheric flexure, crater formation, relaxation and distribution, characterize regolith properties, search for evidence of cryovolcanic activity (e.g. ponds) etc.
  Ganymede: Test models of grooved terrain formation, measure fault geometry, characterize crater formation, relaxation and distribution, lithospheric flexure, determine global stratigraphy, characterize regolith properties and sublimation processes, search for evidence of cryovolcanic activity (e.g. source vents, flow fronts, calderas) etc.
  Callisto: characterize regolith properties, sublimation and transport processes, search for evidence of cryovolcanic activity (e.g. source vents, flow fronts), characterize crater formation and degradation processes and distribution, etc.

- *Measurement 1ABCD2*: Nested monochromatic imaging of selected target areas at a range of resolutions down to submeter/pixel scale (will depend on available orbit) (60˚-75˚ incidence).

  Justification:
  Europa: Characterize regolith properties, search for evidence of current or past cryovolcanic activity (e.g. plumes, flow fronts). Test models of ridge and band formation, chaos formation (e.g., diapiric or melt-through), primary and secondary crater morphology and formation, small crater distribution, etc.
  Ganymede: Test models of grooved terrain formation, characterize fault geometry, determine small crater distribution (especially on dark terrain),

characterize regolith properties and sublimation processes, search for evidence of past or current cryovolcanic activity (e.g. source vents, plumes, flow fronts) etc.

Callisto: Determine small crater distribution, characterize crater and pit formation and degradation processes, characterize regolith properties, sublimation and transport processes, search for evidence of cryovolcanic activity (e.g. source vents, flow fronts), etc.

- *Measurement 1ABCD3*: Monochrome global (albedo) mapping at better than or equal to 10 m/pixel. Phase angle less than 30˚ (as near as possible close to poles).

Justification:

Europa: Determine global stratigraphy (when tied to topogaphy), characterize changes in albedo with age, surface processes and location, test models of ridge and band formation, chaos formation, crater formation, search for evidence of past or current cryovolcanic activity (e.g. triple bands, plumes) etc.

Ganymede: Test models of conversion from dark to grooved terrain, characterize crater formation, determine global stratigraphy, characterize changes in albedo with age, surface processes and location, characterize regolith properties, sublimation and gradation processes, search for evidence of past or current cryovolcanic activity (e.g. source vents, flow fronts) etc.

Callisto: Characterize crater formation, determine global stratigraphy, characterize changes in albedo with age, surface processes and location, characterize regolith properties, sublimation and gradation processes, search for evidence of cryovolcanic activity (e.g. flow fronts) etc.

- *Measurement 1ABCD 4*: Multispectral global mapping (minimum 3 colors) at better than or equal to 100 m/pixel. Selected areas at or better than 30 m/pixel. Phase angle less than 30˚ (except near poles). Violet, green, IR.

Justification:

Europa: Characterize changes in color with age, surface processes and location, test models of ridge and band formation, chaos formation, crater formation, search for evidence of cryovolcanic activity (e.g. triple bands) etc.

Io: Monitoring of the spatial and temporal variability of Io's dynamic geological activity

Ganymede: Characterize polar caps, search for evidence of cryovolcanic activity (e.g. source vents, flow fronts). Investigate dark floor/dark ray craters (e.g., search for evidence of impactor provenance), palimpsests, etc.

Callisto: Investigate anomalous global color variations, characterize crater formation, search for evidence of cryovolcanic activity etc.

Objective 2. Identify and characterize potential landing sites for future missions

-- Investigation 2A: Evaluate surface structure, characteristics and properties at local scales (spatial scales of decimeters)

- *Measurement 2A1*: In addition to above scientific requirements, super-high resolution monochrome images of selected target areas (with intermediate context imaging) down to 25 cm/pixel scale at incidence angles ~60˚-70˚.

Remote Sensing: Geology & Geochemistry

Objective 1. Determine the coupled compositional evolution of the Jovian Satellites: Determine the composition, origin, physical state, and distribution of surface materials of all four Galilean Satellites

-- Investigation 1A: Identify major and minor surface components, distributions, geological ages, including abiotic and biotic organic molecules, trapped volatiles. Do this on a global scale, at a resolution comparable to the scale of the geological processes and composition.
- *Measurement 1A1*: Near IR (many species): wavelength range of 1 – 5 µm; spectral resolution of 300; spatial resolution <100 m; spatial coverage of 90%
- *Measurement 1A2*: Near IR (higher spectral resolution to identify hydrated materials): wavelength range of 1.2 – 2.5 µm; spectral resolution of 1000; spatial resolution < 100 m; spatial coverage of 5% (targeted)
- *Measurement 1A3*: Visible (O_2; coloring agents): wavelength range of 0.4 – 1.0 µm; spectral resolution of 200; spatial resolution <100m; spatial coverage of 90%
- *Measurement 1A4*: UV (SO_x, O_3, H_2O_2, OH…): wavelength range of 0.2 – 0.4µm; spectral resolution of 40; spatial resolution <100m; spatial coverage of 90%
- Measurement 1A5: Mid IR (fundamental modes of e.g., organics) wavelength range of 5 to ≥ 8µm; variable spectral resolution; spatial coverage of 90% (especially useful during nighttime)
- *Measurement 1A6*: X-ray (major element abundances to 5%): wavelength range < 0.01 µm; spatial resolution of 10km (radiation noise may be problematic)
- *Measurement 1A7*: Luminescence, Cerenkov radiation from the surface (major elements and perhaps molecules): wavelength range of 0.2 – 1.5µm; spectral resolution of 300; nighttime observation without Jupiter light, high sensitivity needed.

-- Investigation 1B: Characterize currently and recently geologically active areas, e.g., by short-lived chemical markers, thermal anomalies, change detection, plumes
- *Measurement 1B1*: Thermal: wavelength range of 8 to 50µm, spectral resolution of 2, spatial resolution <300m, spatial coverage of 90%
- *Measurement 1B2*: UV (SO_x, O_3, H_2O_2, OH…): wavelength range of 0.2 – 0.4 µm; spectral resolution of 40; spatial resolution <100m; spatial coverage of 90%; number of times to repeat the observation = few
- *Measurement 1B3*: Visible (O_2): wavelength range of 0.55 to 0.65µm; spectral resolution of 200; spatial resolution <100m; spatial coverage of 90%, number of times to repeat the observation =few
- *Measurement 1B4*: Near IR (many spectrally active species): wavelength range of 1 to 5µm; spectral resolution of 300; spatial resolution <100m; spatial coverage of 90%; number of times to repeat the observation =few

-- Investigation 1C**:** Characterize exogenics vs. endogenic processes via spatial distribution patterns or other characteristics such as time variability (diurnal or longer timescales) of surface chemistry

- *Measurement 1C1:* Similar measurements to investigation 2, but T=several times of day, monthly

-- Investigation 1D: Map regolith thermophysical properties
- *Measurement 1D1:* Thermal; wavelength range = 8 - 50µm, spectral resolution =2, spatial resolution =<300m, spatial coverage =90%; number of times to repeat the observation =several times of day esp. night
- *Measurement 1D2:* Bolometric albedo: (wavelength range of 0.3 to 3 µm; broad illumination geometry coverage, good absolute calibration)

-- Investigation 1E**:** Determine heat flow on Europa and Io to investigate their coupled thermal evolution. A Europa heat flow heat flow observation would have very high science value and would be placed at higher priority but is a very difficult measurement. Further study is required to evaluate its feasibility using remote heat balance measurements. The sensitivity of temperatures to heat flow is greatest at the poles, so these are high priority.
- *Measurement 1E1:* Thermal: wavelength range =8 - 100µm, spectral resolution =2, spatial resolution =<300m, spatial coverage =90%; number of times to repeat the observation =several times of days, esp. night
- *Measurement 1E2:* Bolometric albedo: (wavelength range = 0.3 -3µm; broad illumination geometry coverage, good absolute calibration)
- *Measurement 1E3:* Microwave for subsurface temperatures. Might probe heat flow directly by measuring the subsurface temperature gradient, but emissivity and conductivity uncertainties, and possible solid-state greenhouse effects might complicate interpretation.

-- Investigation 1F**:** Determine temperature-dependent physical and chemical stability of surface components) e.g. to determine sublimation rates, chemical reaction rates)
- *Measurement **1F1***: Thermal: wavelength range = 8-50µm, spectral resolution = 2, spatial resolution =<300m, spatial coverage =90%; number of times to repeat the observation =several times of day, esp. night. Polar coverage for volatile cold traps

-- Investigation 1G**:** Map isotopic components that elucidate fractionation processes
- *Measurement 1G1:* Near IR (especially CO_2, SO_2): wavelength range =1-5 µm; spectral resolution = >500?; spatial resolution =<100m; spatial coverage =90%

-- Investigation 1H**:** Map regolith photometric properties
- *Measurement 1H1*: wavelength range =0.3 – 3 µm; spectral resolution =2; broad illumination geometry coverage, good absolute calibration

Notes
Signal-to-noise ratios must be adequate to detect expected species.
Note: Spatial resolution requirements do not apply to Io during the baseline mission.

Other objectives

Engineering characterization of potential landing sites for future missions.
E.g. “rock” abundance (thermal IR), surface roughness, slopes…

Ancillary remote sensing objectives:
Outer satellite(s) flyby on approach??

Additional Considerations

We have a strong preference for a scan platform rather than nadir-fixed instrumentation because:

- Require ability to view surface targets at multiple viewing geometries
- Target interesting features several times for follow-up studies
- Enable observations of anything while thrusting
- Enables observations of other targets while orbiting the icy moons

Io is a high priority target because:

- Plasma source for the magnetosphere, icy moon environments
- Understanding tidal heating on Io (steady-state? Variable?) is key to understanding tidal heating of the icy moons
- Io is a “naked Europa”
- Io is of great intrinsic interest, and moderate spatial resolution, high time resolution observation from JIMO can or the first time allow direct study of dynamic volcanic phenomena as they evolve.

Co-registering data sets, concurrent where possible
High-inclination orbits high priority: we want to see Europa’s poles!
Low altitudes preferred for the laser spectroscopy, X-ray, otherwise altitude determined by coverage, resolution constraints.
For most investigations in our group, ~ noon/midnight orbit orientation preferred

High-power/high capability instruments

Imaging spectrometer, <100m spatial, 0.4 - 5μm, R=300 (high data rate, high power for cooling?)
5-8μm laser spectrometer (high power)
Thermal mapper (high power for array cooling?)
X-ray spectrometer (high power for array cooling?)

Surface Geophysics & Geochemistry

Objective 1: Determine and quantify the processes that are currently acting to shape or re-shape the surfaces of Jupiter's icy moons

-- Investigation 1A: Search for changes in surface morphology during JIMO and since Voyager
- *Measurement 1A1*: Detect and localize deformation events including impacts, fracturing, flows, relaxation and mass wasting
- *Measurement 1A2*: Detect and map surface changes as a function of time (venting, sublimation/deposition, non-synchronous rotation)
- *Measurement 1A3*: Measure thermal anomalies due to active deformation or active/recent vertical transport

-- Investigation 1B: Quantify mass transport to and from the surface
- *Measurement 1B1*: Measure fluxes of matter and energy into and out of the surface. Characterize exogenic and endogenic sources (impactors, dust, gas, brines, and charged particles)
- *Measurement 1B2*: Measure the composition of dust and gas in the environs of the satellites

-- Investigation 1C: Determine the forces that drive morphological change and mass transport
- *Measurement 1C1*: Determine correlation of morphological change, mass transport and seismicity with driving mechanisms such as tidal motion, convection, nonsynchronous rotation, libration, static topography, impacts and thermal stress

Objective 2: Determine and quantify the processes that are altering the physical and/or chemical state of the surface materials

-- Investigation 2A: Search for changes in surface chemical composition during JIMO and since Voyager
- *Measurement 2A1*: Detect and map changes in surface as a function of time
- *Measurement 2A2*: Analyze the chemical composition of material from the surface via ejected dust and/or surface sampling techniques
- *Measurement 2A3*: Measure diurnal variations in surface properties (i.e. condensation and sublimation)
- *Measurement 2A4*: Measure magnetosphere-induced variations in surface properties

-- Investigation 2B: Characterize chemical and energy fluxes to and from the surface and the relative endogenic versus exogenic components
- *Measurement 2B1*: Measure the particles and fields that characterize the exogenic fluxes in a system wide observation, all the way in to Io

- *Measurement 2B2*: Measure the composition of dust and gas in environs of the satellites to constrain surface composition and impactor flux
- *Measurement 2B3*: Measure the chemical composition of materials in the shallow subsurface to determine fluxes

-- Investigation 2C: Determine the rates of radiation processing of surface materials (2nd Priority)

- *Measurement 2C1*: Measure the relative abundance of radiolytically produced surface materials

-- Investigation 2D: Determine rates of gardening (2nd Priority)

Objective 3: Ground truth surface properties

-- Investigation 3A: Determine physical properties of the surface.

- *Measurement 3A1*: Determine the mechanical properties of surface material (i.e. density, porosity, impurities, bulk and elastic modulii)
- *Measurement 3A2*: Characterize microstructure of ice (2nd Priority)

-- Investigation 3B: Determine chemical composition of the surface

- *Measurement 3B1*: Quantify icy and non-icy chemical composition
- *Measurement 3B2*: Measure biologically significant chemical species (electron acceptors, electron donors, carbon sources, nutrients).
- *Measurement 3B3*: Measure pH, redox potential, electrical conductivity (2nd Priority)
- *Measurement 3B4*: Measure abundance of radiolytically processed materials (2nd Priority)
- *Measurement 3B5*: Measure isotopic ratios (2nd Priority)

-- Investigation 3C: Determine thermal properties of the surface, including heat flow

- *Measurement 3C1*: Measure temperature (surface, subsurface) and heat flow
- *Measurement 3C2*: Measure thermal inertia
- *Measurement 3C3*: Measure thermal conductivity

Issues

-- Platform issues

- Landed package(s) needed
- Subsatellite desirable for gravity & magnetics
- The spacecraft will need considerable autonomy to be able to identify and react to significant events occurring on the surfaces of the satellites
- Scan platform will likely be required

-- Orbit characteristics

- Revisiting locations implies conflicting orbit objectives (same time of day for change detection, different times for tidal correlations)
- Global coverage

-- Make laboratory measurements of fundamental physical and chemical properties at satellite surface conditions
  - Thermal, mechanical, electromagnetic properties of icy satellite materials

Field & Plasma Science

Requirements
Electromagnetically clean measurement platform.
Full sky coverage for particle detectors.
Stable platform or knowledge of pointing to level required by Magnetometer.
High inclination orbits for moons.
High capability instruments:
High data rate: Plasma wave and radio sounder (Mbps), particle detectors (Mbps), X-ray (Mbytes per imaging spectrum).
High power: radio sounder (many kilowatts), particle and dust detectors (tens of watts), X-ray (unsure but tens of watts).

Baseline field and plasma measurements =
Magnetic field (resolution of 60 vectors/s) + particle measurements (electron + ion, 10 eV to > 10 MeV with a distribution function every 10 s or better) + plasma wave measurements (electric + magnetic with a spectrum every 10 s or better and some selected waveform data)

Objective 1 (priority 1): Determine the presence and distribution of subsurface liquid water in the icy satellites

-- Investigation 1A: (Priority 1) Study the natural EM inductive response of moons
  - *Measurement 1A1*: (Priority 1) Measure the magnetic field with global coverage.

-- Investigation 1B: (Priority 1) Study the electromagnetic interaction of the satellites with the Jovian plasma to understand external currents.
  - *Measurement 1B1*: (Priority 1) Baseline field and plasma to understand external currents
  - *Measurement 1B2*: (Priority 1) Theory component: Model the interaction of magnetosphere with satellites to separate internal (induced) and external (local currents) fields. Model the induction signature in terms of models of the interiors.
  - *Measurement 1B3*: (Priority 2) Measure the electric field. Delta-t = 10 s.
  - *Measurement 1B3*: (Priority 3) Measure the electric currents. Delta-t = 10 s.

-- Investigation 1C: (Priority 2) Actively probe the ice crust.
  - *Measurement 1C1*: (Priority 1) Measure return echoes from low frequency radar sounder (sweep frequencies over 100 kHz to 40 MHz).

Objective 2: (Priority 1) Determine the nature of the satellite-magnetosphere interactions including the radiation environment of the icy satellites. (expanded JIMO objective 3)

-- Investigation 2A: Priority 1) Map changing radiation environment of satellites at all latitudes and longitudes.
  - *Measurement 2A1*: (Priority 1) Baseline field and plasma and energetic neutrals.
  - *Measurement 2A2*: (Priority 1) Make remote observations of energetic neutrals and X-rays.

-- Investigation 2B: (Priority 1) Structure and dynamics of ionospheres of satellites.
- *Measurement 2B1*: (Priority 1) Baseline field and plasma measurements

-- Investigation 2C: (Priority 1) Structure and dynamics of Ganymede's magnetosphere.
- *Measurement 2C1*: (Priority 1) Baseline field and plasma measurements
- *Measurement 2C2*: (Priority 2) Remote observations of energetic neutrals and X-rays.

-- Investigation 2D: (Priority 2) Study plasma pick-up, wave particle interactions and particle acceleration processes.
- *Measurement 2D1*: (Priority 1) Make baseline field and plasma observations and neutrals.
- *Measurement 2D2*: (Priority 2) Measure energetic neutrals.

-- Investigation 2E: (Priority 2) Study satellite related auroras
- *Measurement 2E1*: (Priority 1) Measure auroras in the atmospheres of satellites (IR, UV, X-rays)
- *Measurement 2E2*: (Priority 2) Remote IR, UV imaging of satellite footprint auroras in Jupiter's polar regions.

Objective 3: (Priority 1) Determine the surface composition and properties of the ices of the icy satellites

-- Investigation 3A: (Priority 1) Study the elemental composition of the surface from remote observations
- *Measurement 3A1*: X-ray spectral imaging

-- Investigation 3B: Study the composition of ejected material.
- *Measurement 3B1*: (Priority 1) Neutral gas composition (up to at least 300 AMU with mass resolution of 500 M/Delta-M).
- *Measurement 3B2*: (Priority 2) Baseline field and plasma + ion composition (ionospheric and pickup ions to ~100 AMU, 0.1% abundance & M/Delta-M >> 20)
- *Measurement 3B3*: (Priority 2) Dust cloud composition (higher priority if complex organics can be done well).

-- Investigation 3C: (Priority 2) Study the impurities, brines and thermal profile of ice
- *Measurement 3C1*: (Priority 1) Measure the subsurface conductivity from low frequency sounder radio echoes.

Objective 4: (Priority 2) Jovian Magnetosphere

-- Investigation 4A: (Priority 1) Structure and dynamics of Jupiter's magnetosphere including periodicities.
- *Measurement 4A1*: Baseline field and plasma measurements

-- Investigation 4B: (Priority 1) Interaction of solar wind with Jovian magnetosphere.
- *Measurement 4B1*: (Priority 1) Baseline field and plasma measurements with upstream solar wind capabilities
- *Measurement 4B2:* (Priority 1) Measure Jovian emissions (energetic neutral and charged particles, radio waves, dust, aurora).

-- Investigation 4C: (Priority 2) Coupling of magnetosphere/ionosphere including the upper atmosphere
- *Measurement 4C1*: Baseline field and plasma measurements

-- Investigation 4D: (Priority 2) Auroral physics including local plasma measurements in the equatorial plane.
- *Measurement 4D1*: Observe Jovian aurora at IR, UV, X-ray and radio wavelengths **continuously** while making in situ measurements of the magnetosphere.

Objective 5: (Priority 2) Deep internal structure

-- Investigation 5A: (Priority 1) Study the inductive response of the interiors of the icy moons and detect a core using the changing field of Jupiter.
- *Measurement 5A1*: Baseline field and plasma measurements

-- Investigation 5B: (Priority 1) Study the internal magnetic field of Ganymede to high order and degree.
- *Measurement 5B1*: Baseline field and plasma measurements

-- Investigation 5C: (Priority 2) Study the secular variation in Ganymede's magnetic field
- *Measurement 5C1*: Baseline field and plasma measurements over three months or 1onger (three months implies high accuracy of internal field measurements)

Objective 6: (Priority 3) Determine the influence of Io on the Jovian magnetosphere

-- Investigation 6A: (Priority 1) Remotely observe the structure and dynamics of Io's torus.

-- Investigation 6B: (Priority 2) Study the relationship of volcanic activity to the variability of Io's torus and magnetospheric dynamics.

-- Investigation 6C: (Priority 2) Study the interaction of Io with its torus through remote sensing.
- *Measurement 6C1*: Io auroras and airglows

-- Investigation 6D: (Priority 3) Study the interaction of Io with its torus (extended mission).

-- Investigation 6E: (Priority 4) Infer the interior structure from electromagnetic induction (extended mission).

-- <u>Investigation 6F</u>: (Priority 4) Better limits on the internal field of Io (extended mission).

Interiors and Subsurface

The purpose of these objectives is to emphasize their essential role for Jupiter system science. If they are not done on JIMO then they must be done on another mission to take fullest advantage of what JIMO tells us about the Jupiter system.

Objective 1 (1st equal Priority): to determine the extent of global differentiation of the icy moons through evaluation of the moments of inertia

-- Investigation 1A: (1st priority): Study of the low order gravity (especially degree 2) and associated topography
- *Measurement 1A1*: Static J_2 and C_{22}; constraints on nonhydrostatic components from higher harmonics and test of hydrostaticity. At 1×10^{-7} accuracy.
- *Measurement 1A2*: Determination of degree 2 static topography to at least ten meter accuracy

-- Investigation 1B: (1st priority) : Determination of obliquity & precession of the spin pole.
- *Measurement1B1*: Pole position to about 10m accuracy.

Commentary: The moments of inertia determined by Galileo are more uncertain than often acknowledged because they assume hydrostatic conditions. Separate determination of all degree 2 terms will eliminate most but not all this of ambiguity. Determination of pole position together with gravity will provide moments of inertia directly. Determination of degree 2 topography provides additional information on degree of non-hydrostatic conditions.

Objective 2 (1st Equal Priority): to determine the presence of oceans

-- Investigation 2A: (1st priority): through the study of the response (gravity, topography) of these bodies to tides.
- *Measurement 2A1*: Determination of the surface motion that correlates with the eccentricity tidal potential to 1 meter accuracy. (Equivalently, the eccentricity tidal k_2 and h_2 at accuracy 0.01)

Commentary: Although most believe that these bodies have oceans, this remains to be confirmed. The clearest confirmation comes from the difference in the expected response (tidal topography) between bodies with and without oceans. In the case of Europa, the expected difference is enormous and easily observed.

Objective 3 (1st Equal priority): to constrain the thickness of ice over the oceans (especially for Europa)

-- Investigation 3A: (1st priority): through the study of the response (gravity, topography, libration) of these bodies to tides.

- *Measurement 3A1*: Determination of eccentricity tidal response to meter accuracy. (This includes but is not restricted to degree 2 response). This includes determining k_2 and h_2 to accuracy of 0.005 at all the satellites. In terms of percentage uncertainty in the result, this is a higher measurement requirement at Europa than at the other icy moons.
- *Measurement 3A2*: Determination of the libration amplitude to 10-m accuracy for Europa.

-- Investigation 3B: (1st equal priority): through the induction response (magnetic field produced by Jupiter's time varying field).

- *Measurement 3B1*: Determination of induction response at orbital (as well as Jupiter rotation) time scales for all the satellites.

-- Investigation 3C: (2nd priority): through passive seismology

- *Measurement 3C1*: Geophone on Europa's surface, to detect differential travel times. (Relying on the seismic signals from tidal cracking of the ice)

-- Investigation 3D: (2nd priority): through gravity and topography.

- *Measurement 3D1*: Gravity and topography at high harmonic degree (~degree 20)

-- Investigation 3E: (3rd priority) : through constraints on non-synchronous rotation.

- *Measurement 3E1*: Imaging of surface features.

Commentary: Ice thicknesses for Ganymede and Callisto are not highly uncertain. The percentage uncertainty for ice thickness on Europa is very large at present. It is important to have many different complementary approaches to this problem, each of which will introduce uncertainty through uncertain material parameters (e.g., rigidity, conductivity). The combination of approaches will reduce the ambiguity. Looking at the harmonics other than those that will dominate for a simple uniform ocean provides information on lateral variation of the ocean or material properties.

Passive seismology is given lower priority because of concern that it may not work. Active seismology is regarded as a high pay-off but also high risk option.

Objective 4 (2nd Priority): Determine the abundances of major elements in Jupiter (especially oxygen)

-- Investigation 4A: (1st priority): through in situ measurement at >100 bars in Jupiter's atmosphere

- *Measurement 4A1*: In situ determination to 0.1 solar. The atmosphere group have provided a more detailed description of the goals of in situ measurements.

Commentary: An essential part of Jupiter system science. The composition of Jupiter itself is relevant to our understanding of the composition of the Galilean satellites. Not an essential part of JIMO.

Objective 5 (3rd Priority): to determine the orbital evolution of Europa and Ganymede (and Io?)

-- Investigation 5A: through navigation (radio science)
  - *Measurement 5A1*: Secular acceleration of all the icy moons to 5m/yr^2 (corresponds to ~ a few meters in orbit location). Particularly important for Europa.

-- Investigation 5B: (2nd priority): Constraint on the tidal amplitude of Io (from Europa orbit) to 10m.

-- Investigation 5C: (2nd priority): Constrain (i.e., bound above) the imaginary part of the tidal Love number (i.e., the tidal phase shift) at Europa.

Commentary: Standard tidal models assume uniform orbital expansion of Io, Europa and Ganymede. However, we have no direct confirmation of these models and some reason to expect they may be wrong because of time-variable tidal dissipation. Thus, direct detection of the time rate of change of mean motion is needed and constrains the history of the system and the heating rates within these bodies. The expected secular acceleration corresponds to a shift in the orbital angular position of ~tens of meters in a year. However, models and existing observations allow for a large range of possible values including positive values of dn/dt (i.e., satellite spiraling in to Jupiter rather than spiraling out).

Objective 6 (3rd Priority): to determine the (intrinsic) internal magnetic fields of the icy moons, especially Ganymede.

-- Investigation 6A:
  - *Measurement 6A1*: Steady component of the magnetic field of Ganymede from orbit, to an accuracy ~0.01 or better of the dipole field.
  - *Measurement 6A2*: Limits on secular variation for Ganymede
  - *Measurement 6A3*: Limits on the steady component of the magnetic field of Europa and Callisto from orbit.

Commentary: Ganymede has a dynamo. A better understanding of dynamos is a part of meeting the fundamental goal of figuring out how planets work, as well as constraining the dynamic state of the deep interior. It is also desirable to look out for permanent magnetism (which would show up as a deviation from the expected power spectrum of the field).

Objective 7 (3rd Priority): to characterize the non-hydrostatic gravity & topography at regional to global scales

-- Investigation 7A: (1st priority): through study the gravity and associated topography

- *Measurement 7A1*: Gravity at degree *l* ~ 4 to 12. (In reality, measurement to degree 20 is likely but we do not need to enforce this requirement in order to get the high priority science.)
- *Measurement 7A2*: Long wavelength topography at 10m vertical accuracy.

Commentary: The actual harmonic reached depends on the amplitude of the gravity field. The silicate component probably dominates the gravity because it can support stresses that are ~two orders of magnitude larger than the ice component. Detecting the response of the ice or convection of the ice on Europa is highly desirable but cannot be guaranteed.

Objective 8 (4th priority) to determine the heat flow of the icy moons, with emphasis on Europa

-- Investigation 8A:
- *Measurement 8A1*: Bound on heat flow from orbit.
- *Measurement 8A2*: Determination of heat flow at surface of Europa

Commentary: Heat flow is very important but it is unlikely to be large enough on the icy moons to measure remotely. Very thin ice shell models for Europa require heat flows that might be measured remotely, and such a measurement might then test those models. In situ measurement is easier but still difficult and possibly not representative. (There is still doubt about the heat flow on the moon despite in situ measurements).

Objective 9 (5th priority) Gravity and magnetic field of Jupiter

-- Investigation 9A: through emplacing a subsatellite around Jupiter.
- *Measurement 9A1*: Gravity to degree 12.
- *Measurement 9A2*: Magnetic field to degree 12.

Commentary: An essential part of Jupiter system science. Not an essential part of JIMO. The science goals here correspond to possible Discovery or New Frontiers misisons.

Other issues:

1. Orbital inclination. High inclination (or a range of inclinations) is highly desirable.

2. Thrusting continuously or just some of the time? Continuous thrusting is bad for measuring gravity.

<u>Subsurface Science</u>

Objective 1: To determine the volumetric distribution of free water (including brines) within Europa, Ganymede and Callisto.

-- <u>Investigation 1A</u>: Study the subsurface thermal and kinematic factors that control the distribution of free water and how this distribution has changed through time.

- *Measurement 1A1*: Global profiling of thermal, compositional and structural horizons for Europa, Ganymede, and Callisto's icy shells, at <= 5 deg. equatorial separations, at depths from 2 up to 30 km at 100 m vertical resolution, and at depths from 100m – 2 km at 10 m vertical resolution.

-- <u>Investigation 1B</u>: Study the relationship between these thermal and kinematic factors and observed surface features.

- *Measurement 1B1*: Profile thermal, compositional and structural horizons below a suite of representative surface features at depths of 100 m – 2 km, with a horizontal resolution of 1-2 km, and vertical resolution of 10 m.
- *Measurement 1B2*: Map the topography of this suite of surface features in two spatial dimensions with a 10 m horizontal resolution and 1 m vertical resolution, with a no-less-than 5 km swath width along the nadir track.

Objective 2: To determine the means of ice-ocean interchange of material on Europa and where this material could best be sampled by future landed missions.

-- <u>Investigation 2A</u>: Test the hypothesis of direct exchange between any ocean and the icy mantle's cold brittle shell and establish whether there is any direct means for ice-ocean interchange with the shallow subsurface.

- *Measurement 2A1*: Profile thermal, compositional and structural horizons below a suite of representative surface features at depths of 100 m – 2 km, with a horizontal resolution of 1-2 km, and vertical resolution of 10 m.

-- <u>Investigation 2B</u>: Test the hypothesis of indirect exchange with any ocean through the movement of deep ductile ice into the cold brittle shell.

- *Measurement 2B1*: In addition to Measurement I.A.1, map global topography at 10 m horizontal and 1 m vertical resolution.

Objective 3: To determine the geological processes that control the exchange of material in the shallow subsurface (above the annealing depth) of Europa, Ganymede and Callisto.

-- <u>Investigation 3A</u>: Study the physical properties in the shallow subsurface and its relationship to the mapped distributions of surface constituents, physical structures and thermal features.

- *Measurement 3A1*: Map the sub-surface (> 1m) heterogeneity of the regolith, at better than 100 m horizontal resolution, covering at least 50% of Europa, Ganymede, and Callisto, with a minimum swath width of 50 km.

-- Investigation 3B: Study the relationship between geological processes and the physical properties of the regolith.

- *Measurement 3B1*: Global profiling of thermal, compositional and structural horizons for Europa, Ganymede, and Callisto's icy shells, at <= 5 deg. equatorial separations, at depths from 2 up to 30 km at 100 m vertical resolution, and at depths from 100m – 2 km at 10 m vertical resolution.

Atmospheres, Tori, and Rings

Objective 1: To determine the composition, structure, chemistry, and dynamics of Jupiter's atmosphere

-- Investigation 1A: Study the elemental abundances of the planet (Meets Decadal Survey #1, 2, 4, 5, 12)

- *Measurement 1A1*: Measure water (O/H) abundance to 100-bar level at least at one location to accuracy of .001 relative to H_2. Requires *in situ* gas chromatograph/ mass spectrometer.
- *Measurement 1A2*: Measure abundance of ammonia (N/H), neon, H_2S (S/H), D/H, etc. to ~10%. Requires *in situ* gas chromatograph/ mass spectrometer, acoustical measure of helium, para hydrogen.

-- Investigation 1B: Study the winds and dynamics of the planet to determine overall circulation and how it affects atmospheric evolution (Meets Decadal Survey #11, 12)

- *Measurement 1B1*: Measure winds to 100-bar level at least at one location for deep circulation, tied to the interior in an unknown way. Requires in-situ Doppler Wind
- *Measurement 1B2*: Measure the dynamics of individual thunderstorms and cloud features over their life cycles at a resolution of 10 km per pixel with a sampling rate of 10^3 s. Requires visible and near-IR imaging.
- *Measurement 1B3*: Measure the water variability at and above the clouds with global coverage and 100 km spatial resolution. Use 5-micron imaging spectroscopy with spectral resolution R > 3000.
- *Measurement 1B4*: Measure the 3D gaseous ammonia distribution with 5000 km horizontal spatial resolution at 1-5 bars and 200 km resolution at .01-.5 bars. Passive microwave radiometry at 1-5 cm wavelength, possibly using the telecom antenna as a receiver for 1- 5 bar region. Mid-IR (10 microns) for 1 to .5 bar region, R > 2500.

-- Investigation 1C: Study the temperature and energy balance of the planet to better understand what role solar insolation, winds and eddies play in atmospheric circulation and convection (Meets Decadal Survey #2, 6, 11, 12)

- *Measurement 1C1*: Measure the vertical temperature gradient to 100-bar level at least at one location to accuracy of 0.1 K km^{-1}. Requires *in situ* measurement with atmospheric structure instrument.
- *Measurement 1C2*: Measure the poleward eddy heat flux from simultaneous maps of wind and temperature at horizontal scales of 100 km or better. At 7-8 microns, R > 1000. At 14-40 microns, R > 50.
- *Measurement 1C3*: Obtain global temperature maps for vertical temperature structure, waves and horizontal gradients (for deriving thermal wind shears). Limb sensing with 20-40 km vertical resolution is required for lower stratosphere coverage. Pressure range 1–500 mbar. Same spectral requirements as Meas. 2 with global coverage and horizontal scale of 20-40 km at the limb, 100 km global.

- *Measurement 1C4*: Use repeated radio occultations to obtain vertical temperature profiles closely spaced in space and time for investigating wave propagation in the stratosphere and upper troposphere.
- *Measurement 1C5*: Monitor stellar and solar occultations to obtain high vertical resolution temperature structure and composition.

-- Investigation 1D: Study Jupiter's clouds, hazes and precipitation (Meets Decadal Survey #2, 4, 6, 11, 12)

- *Measurement 1D1*: Retrieve global and regional cloud vertical structure from .1 to 5 bars. Requires simultaneous visible and near IR spectral imaging with comparable spatial resolutions, to best identify the locations and composition of the clouds. Resolution sufficient to resolve molecular absorption bands (R > 300). Middle IR spectral imaging (~8 micron) with R > 1000. Far IR spectral imaging with R > 500. *In situ* (nephelometer, net flux radiometer) for single location ground truth.
- *Measurement 1D2*: Measure spatial distribution of precipitation at 1000 km spatial resolution (active RADAR required) at depths of 1-5 bars.
- *Measurement 1D3*: Measure spatial distribution of lightning at spatial resolution of 10 km, from visible or near-IR imaging
- *Measurement 1D4*: Characterize the photochemical hazes from ultraviolet imaging, visible wavelength polarization and infrared mapping (.3 – 5 microns) at multiple incidence angles. R ~50-500, spatial resolution of 100 km.
- *Measurement 1D5*: Search for direct detection of NH_3, NH_4SH and H_20 ice signatures with spatial resolution of 10 km. Requires near through far-IR mapping, R ~20-500.

-- Investigation 1E: Study the composition and chemistry of Jupiter's atmosphere to understand sources and sinks, and dynamics from disequilibrium species (Meets Decadal Survey #4, 5, 6, 11, 12)

- *Measurement 1E1*: Measure the 3D distribution of disequilibrium species, *e.g.,* PH_3, CO using mid and far-IR wavelengths at 100 km resolution. R > 2000-5000.
- *Measurement 1E2*: Measure the para H_2 fraction above the visible clouds. Requires far IR mapping with 100 km spatial resolution and R > 100. *In situ* for ground truth.
- *Measurement 1E3*: Measure the 3D distribution of organic molecules at 100 km spatial resolution with global coverage and spectral resolution R > 10000 in the mid-IR (8-16 microns). Limb spectroscopy with 20-40 km vertical spatial resolution for vertical distribution.

Objective 2: Determine composition, structure, and dynamics of icy moon atmospheres.

-- Investigation 2A: Study the gas composition of both bound and escaping atmosphere to understand surface composition and thereby chemistry for potential life.

- *Measurement 2A1*: *In situ* maps of the densities of the primary and trace species (including CH_4 and possible organics near each satellite. [possible technique: neutral/ion mass spectrometer]
- *Measurement 2A2*: Remote sensing measurement of atmospheric species in emission (e.g., O (1304A, 1356A, 6300A), H (1216A), Na 5890,5896A, K 7665,7699A, etc.) and absorption. [Technique: simultaneous multiwavelength (UV through IR) hyperspectral imaging, R > 2000; spatial resolution ~ 20 km/pixel, and use solar/stellar/radio occultations if possible].

-- <u>Investigation 2B</u>: Study relative strength of source and loss mechanisms (sublimation, ion sputtering, surface venting) for the atmospheric structures to better understand the history of volatile compounds in the solar system.

- *Measurement 2B1*: Map the ion species near the satellite that cause sputtering – where do particles have access to the surface?
- *Measurement 2B2*: Map surface temperature to characterize sublimation source.
- *Measurement 2B3*: Image extended energetic neutral atoms (ENA's) near each satellite.
- *Measurement 2B4*: Remote observations of atmospheric (limb profiles, auroras, etc.) and neutral cloud emissions (FUV+visible) to obtain vertical density structure (scale heights and cloud geometry).

-- <u>Investigation 2C</u>: Study atmospheric variations and dynamics to better understand migration of surface constituents.

- *Measurement 2C1*: Monitor state of atmosphere by repeating observations in Investigations 1 & 2 on frequent, multiple timescales, including local time (dawn-dusk), daily, weekly, monthly, and with respect to the plasma field variations. This would include monitoring gas density at ice cracks, vents, and cryovolcanism locations to assess their activity and accessibility to subsurface water and astrobiological products (for future landers).
- *Measurement 2C2*: Measure temperature and flow patterns of neutrals and ions [technique: multi-wavelength high-resolution UV spectrometer of Doppler broadening].

Objective 3: Determine composition, structure, dynamics and time variability of the atmosphere of Io.

-- <u>Investigation 3A</u>: Study the gas composition of both bound, extended and escaping atmosphere to better understand photochemical and thermochemical processes, and transport of material to the icy satellite surfaces.

- *Measurement 3A1*: Remote sensing of atmospheric species in emission and absorption (SO2 in the UV and IR; S (1300-1500A); see also list in Objective 1, Investigation 1) [technique: UV-IR hyperspectral imaging – see requirements in Objective 1, Investigation 1].

- *Measurement 3A2*: Transport of material from Io to icy satellites (to understand what gets implanted). E.g., measure gradient in neutral emissions in the corona and near neutral clouds to study loss of neutrals.

-- Investigation 3B: Study relative strength of source and loss mechanisms (sublimation, volcanoes/venting, ion sputtering) for the atmospheric structures, and for understanding the transport of material to icy satellite surfaces.

- *Measurement 3B1*: Map volcanoes/venting.
- *Measurement 3B2*: Map surface temperature to determine sublimation source (see Objective 2, Investigation 2).
- *Measurement 3B3*: Remote observations of atmosphere species (limb profiles, auroras, etc.) and neutral cloud emissions.
- *Measurement 3B4*: Remote observations of neutral and plasma species emissions, including Doppler shifts.

-- Investigation 3C: Study atmospheric variations to understand gas dynamics and volcanology.

- *Measurement 3C1*: Variation of volcanic plumes and vents
- *Measurement 3C2*: Neutral emissions in collapse/recovery of eclipsed atmosphere in Jupiter's shadow.
- *Measurement 3C3*: Measure dayside/nightside atmospheric emissions (diurnal variability).
- *Measurement 3C4*: Flow patterns of neutrals and ions via Doppler shifts of emissions (requires high resolution spectroscopy).
- *Measurement 3C5*: Coordinate measurements of global volcanic activity with magnetospheric variability.

Objective 4: To determine the nature of the interaction between magnetosphere, satellites, and Jupiter.

-- Investigation 4A: Study the satellite – magnetosphere interaction to understand the radiolytic production of chemicals important for life.

- *Measurement 4A1*: *In situ* particles and fields measurements around satellites (defer to particles and fields subgroup for these measurements).
- *Measurement 4A2*: Remote observations of surface reflectance signatures of radiolysis products (e.g., H_2O_2, H_2SO_4, etc.) important for potential life.
- *Measurement 4A3*: Remote observations of atmosphere emissions (auroras), particularly temporal series spanning at least one Jupiter rotation.
- *Measurement 4A4*: Remote observations of plasma emissions near the satellites, including Doppler shifts.
- *Measurement 4A5*: Temporally extended measurements of neutral and ion emissions from multiple vantage points (e.g., an elliptical orbit with global view at apoapse and *in situ* plasma measurement near the satellite).

-- Investigation 4B: Study the formation processes of the satellite footprints and wakes in the Jovian polar atmosphere to understand the elctrodynamic circuit connecting them.

- *Measurement 4B1*: Jovian auroral emissions from the satellite footprints and wakes, in conjunction with the satellite auroras and *in situ* plasma measurements (i.e., both in ionospheres and upstream and downstream from the satellites).
- *Measurement 4B2*: Measure the charged particle content of flux tubes connecting Jupiter and the satellites via remote (auroras) and *in situ* observations (particles and fields).
- *Measurement 4B3*: Measure variability of both the satellite and Jovian auroral emissions simultaneously (or near in time).

-- Investigation 4C: Study generation of Jupiter's (non-satellite) auroral emissions and their effects on the atmosphere.

- *Measurement 4C1*: Jovian aurora morphology and brightness, in conjunction with *in situ* plasma measurements (see particles and fields group). Simultaneous observations of UV, near- and mid-IR emissions (H_2, H_3^+, CH_4), which also measure of the heating of the neutral atmosphere by auroral processes. [technique: X-ray – IR imaging spectroscopy].
- *Measurement 4C2*: Determine atmospheric winds as a function of altitude to characterize magnetosphere-ionosphere-atmosphere angular momentum transfer. This can be done for example by high spectral (R>100000) and spatial resolution measurements of Lyman alpha line profiles.
- *Measurement 4C3*: Measure the CH_4 homopause altitude in auroral and non-auroral regions to determine auroral effects on the stratosphere.
- *Measurement 4C4*: Measure upper atmospheric composition and temperature structure vs. latitude and longitude.

Objective 5: Structure, composition, energy budget, and variability of satellite tori.

-- Investigation 5A: Understand the mechanisms by which mass and energy flow through the system.

- *Measurement 5A1*: Image maps of plasma EUV emissions via remote sensing

-- Investigation 5B: Define the mechanisms that control the radial, azimuthal (local time and system III) and magnetic field aligned distributions of plasma and temperature.

- *Measurement 5B1*: 2-d (latitude and radius) image maps of plasma EUV emissions via remote sensing with synoptic coverage.
- *Measurement 5B2*: Resolve ion velocities [possible technique: high-resolution spectroscopy]

Objective 6: Structure and particle properties of the Jovian ring system

-- Investigation 6A: To determine the size distribution in each ring component

- *Measurement 6A1*: Broad-band imaging of each ring component at visual to near IR (0.4 to 2 micron) wavelengths and multiple phase angles. Include phase angles > 178 degrees and < 5 degrees. Phase angle sampling < 10 degrees. Signal-to-noise > 100. Spatial resolution < 10 km. Field of view > 10,000 km.
- *Measurement 6A2*: Visual to IR (0.5 to 5 micron) spectral image cubes of each ring component. Signal-to-noise > 100. Spectral resolution < 0.02 microns. Spatial resolution < 50 km. Field of view > 15,000 km. At least 5 phase angles including < 10 degrees and > 175 degrees.
- *Measurement 6A3*: Far IR emission spectra of the main ring. Signal-to-noise > 100. Wavelength range 5 to 300 microns.
- *Measurement 6A4*: RADAR studies of the main ring and inner satellites. Sufficient sensitivity to detect a ring optical depth of 10^{-6}.

-- Investigation 6B: To determine the 3-D structure Jovian ring system.

- *Measurement 6B1*: Edge-on imaging of the entire ring system < 10 km resolution. Multiple (> 5) phase angles including < 10 degrees and > 170 degrees. Several visual and near-IR wavelengths. Multiple longitudes relative to the nodes of Amalthea's and Thebe's orbits to look for orbital concentrations.
- *Measurement 6B2*: Broad-band imaging of the halo crossing into the Jovian shadow, as viewed from within the shadow. Multiple broad-band filters in the visual and near-IR. Resolution < 10 km. Field of view > 10,000 km.
- *Measurement 6B3*: Fine resolution (< 1 km resolution) imaging of the main ring. Multiple (> 5) phase angles including < 10 degrees and > 175 degrees. Several visual and near-IR wavelengths.

-- Investigation 6C: To determine the composition of the rings and embedded moons.

- *Measurement 6C1*: Visual to IR (0.5 to 5 micron) spectral image cubes of Adrastea, Metis, Amalthea and Thebe. Spectral resolution < 0.02 microns. Phase angle < 20 degrees. Multiple rotational phases.
- *Measurement 6C2*: Visual to IR (0.5 to 5 micron) spectral image cubes of each ring component. Signal-to-noise > 100. Spectral resolution < 0.02 microns. Phase angle < 20 degrees. Spatial resolution < 10 km. Field of view > 15,000 km.

-- Investigation 6D: To complete a comprehensive search for small inner moons of Jupiter, down to a size of 100 m.

- *Measurement 6D1*: Broad-band visual imaging at low phase angles, using long exposures to achieve needed sensitivities. Repeated observations over >1 year to obtain well-defined orbits.

-- Investigation 6E: To study time-variations in the Jovian ring system.

- *Measurement 6E1*: Repeated broad-band imaging (cf. 6.1.1) at 6- to 9-month intervals during a period of > 2 years.

Atmospheric Science Appendix

Instrumentation Requirements to Meet Atmospheric Science Objectives

Our science objectives require:

- **Spectroscopic capabilities** between 0.001 – 40 μm, with a range of spectral resolutions. In the UV, visible and near-infrared, a spectral resolution ($R = \tilde{\lambda}\Delta\lambda$) of at least 2000 is required. In addition, a spectral resolution sufficient to resolve Doppler effects of a few km/sec at selected wavelengths is desired. In the mid-infrared, R ~ 10,000 is required to detect Jovian stratospheric emissions (Objective 1, Investigation 5, Measurement 3).

- **Ultra-narrow band imaging** between 0.3 – 5.2 μm, with a spectral resolution of ~ 300.

- **Spatial resolution** at Jupiter of 10 km/pix for localized studies, 100 km/pix for general studies. Spatial resolutions at the icy satellites must be 20 km/pix or less for the imaging spectroscopy.

- **Energetic Neutral Atom Imager** to observe neutral H, O, and S near the icy satellites and in the circumplanetary environment.

- **Neutral Ion Mass Spectrometer** with enough sensitivity to measure both the primary constituents and trace species in the icy satellite atmospheres ($1 < n < 100$ amu).

Special Considerations

- We recommend an **atmospheric probe** to make *in situ* measurements of the oxygen abundance and deep winds on Jupiter. This is in support of our Objective 1, Investigations 1-5, as well as the 2nd Priority Objective of the Interiors Working Group. NOTE: the Probe is being proposed as an item that would be carried along as part of the JIMO mass margin until Phase C. If, at that time, there is enough mass available to support the Probe, then it would fly as part of the JIMO. However, if there is not enough mass available to support the Probe, it would be removed from the JIMO mission and saved for a later (TBD) mission to Jupiter. Thus, the Probe development efforts from Phases A and B (and before) would not be wasted. In the non-Probe scenario, all of our Jupiter atmospheric science objectives could still be met (albeit at pressure levels much lower than 100 bars), with the exception of determining the equilibrium oxygen abundance.

- Several of our required instruments, such as imaging and high resolution spectrographs or ultra-narrow band imagers, will use large format arrays and therefore will require a **high data rate**. In addition, the mid-to-far-infrared instrument should be actively cooled, resulting in a **high power requirement**.

- The use of the telecommunication antenna on JIMO as a **passive radiometry instrument** is a clever approach that should be considered. Such an instrument could be used to measure the ammonia abundance between 1-5 bars (*i.e.*, below the NH_3 condensation level), thereby addressing Objective 1, Investigation 2, Measurement 4.

- The use of a high-power, active **SAR (Synthetic Aperture Radar) system** would enable the *direct detection* of precipitation on Jupiter for the first time, thereby addressing Objective 1, Investigation 4, Measurement 2.

- Many of our high-level science objectives require **multi-wavelength, simultaneous** observations. Thus, the instruments on JIMO must be bore-sighted, residing on a scan platform. Heavy restrictions on simultaneous observations made with more than one instrument would be detrimental to many of our science objectives.

- The orbital constraints of the JIMO spacecraft should be such that there is some opportunity for the **remote sensing of Jupiter's and the satellites' polar region(s)** with the JIMO instrument suite. The study of polar vortices is critical for the understanding of Jovian dynamics. In addition, such a viewing geometry is highly desirable for the study of the auroral regions of Jupiter and the satellites. Higher altitude or elliptical orbits of the spacecraft around the icy satellites are needed for the global views required to study the satellite aurora morphology.

- Satellite closest approaches for in situ measurements of the atmospheres need to be <20 km.