JPL Studies in Support of the SWOT Mission

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JPL Internal Investment on SWOT

- JPL “Team-X” end-to-end mission assessment, including cost
  - Preliminary assessment: no show stoppers, but several risk items identified
- Experiment to determine near-nadir scattering characteristics of rivers (D. Moller, PI)
- Studies to assess feasibility of next-generation radiometer corrections of wet tropospheric delays (S. Brown)
- Internal studies and contract to Ball Aerospace to assess one of the primary risk areas: power generation with minimal attitude control system disturbance
- JPL will submit an IIP proposal (L-L Fu, PI) to further address outstanding technology risk areas
Building the baby carriage

First comes love,
Then comes marriage,
Then comes baby in a baby carriage...

(American nursery rhyme)
The marriage penalty...

- Ocean + land data collection >double required transmit energy
- Non-sun synchronous orbit is harder than 6am/6pm sun sync
  - Solar panel size must increase to compensate for eclipse time
  - Optimal solar panel orientation requires continuous solar panel rotation about 2 axes, **but** solar panel rotation disturbs the spacecraft attitude, leading to measurement errors
  - Battery size must increase
    ⇒ Need new approach to power generation
- Data collection over land and ocean increases data volume and downlink rate beyond currently affordable capabilities
  ⇒ Need onboard processing of ocean data to reduce downlink spatial resolution to 1 km x 1 km
- Higher orbit + higher solar panel mass requires a bigger launcher
  - Launcher probably in the Delta-II, Ariane class
  - Minotaur IV or Taurus launch may not be feasible
A joint power-attitude/control strategy

• Solar panel motion can couple directly to the attitude control system knowledge error, leading to systematic (i.e., not random) height and slope errors
  → An optimal ACS strategy must restrict solar panel motion to just a few times/orbit

• For stationary solar panels, the angle between the sun and the solar panel must be adjusted as few times per orbit as possible
  - For a 78 deg inclination orbit, it is best to adjust solar panel orientation at higher latitudes, since higher latitudes are visited preferentially
SWOT Mission Solar Array Sizing

- **Spacraft assumption:** Ball BCP-2000 (used for QuikSCAT, CloudSat,…)
- **Orbit Parameters**
  - Altitude: 993 km *(not critical)*
  - Inclination: 78°
  - Period: 105 minutes
  - Beta Angle: 0° to ±90°
  - Eclipse Duration: 0 to 35 minutes
  - Sun Range (min): 0.983 AU (near winter solstice)
  - Sun Range (max): 1.016 AU (near summer solstice)
- **Loads**
  - Bus: 750W *(varies depending on data and telecom requirements)*
  - Payload: 562W
- **Vehicle Attitude**
  - Nadir-pointed, maintaining interferometer payload baseline orthogonal to velocity
  - No sun-nadir (a.k.a., yaw) steering
- **Caveats**
  - Thermal behavior of the various options not modeled; could have second-order affects on sizing analyses
  - Analyses assume no shadow affects on the solar array at any point in the orbit
SWOT Solar Array Configuration #1
Single-Axis Articulation

- Flat panel, trailing bus, conventional solar array technology
- Single-axis articulation, articulate only over polar regions
- Worst-case orbit
  - Beta angle = 0°
  - Eclipse duration = 35 minutes
- Description of operation
  - Assume conventional stowage and deployment methods
  - Over polar regions, solar array rotates about the x-axis (velocity vector) to preposition into fixed orientation for optimal power generation during subsequent pole-to-pole pass.
  - Array off-sun angle reaches 0 degrees as vehicle passes over equator and is near 90 degrees while vehicle is over polar regions.
- Solar Array capability (raw) meets end of life requirements with 25% margin using two solar panels, each of which is smaller than solar panels considered for the NPOES Preparatory Project (NPP) being built at Ball Aerospace.
- Using conventional solar panel technology, a mass penalty > 200 kg will be incurred.
- Potential data loss during panel rotation.
- Battery sizing -- 32 Amp-hour sufficient for worst case eclipse; bus can accommodate larger battery.
SWOT Array Configuration #2
Fixed Differential Orientation, No Articulation

- Two flat panels, trailing bus (beta = 0 to +90) & leading bus (beta = 0 to -90), conventional solar array technology

- Worst-case orbit
  - Beta angle = 0°
  - Eclipse duration = 35 min.

- Panels off-set by fixed angle of XX (ITAR sensitive?), no articulation (XX is the optimal off-set), sun vector bisects the panel off-set angle when beta = 90°

- Description of operation
  - Assume conventional stowage and deployment methods
  - Individual panel off-sun angles vary from XX (ITAR sensitive?) degrees to 90 degrees and above (i.e., back side illuminated) during pole-to-pole passes.

- Solar Array capability (raw) meets end of life requirements with 25% margin using two solar panels, each of which is about 2x the size of the solar panels considered for the NPOES Preparatory Project (NPP) being built at Ball Aerospace.
- No data loss in incurred at any point in the orbit.
- Using conventional solar panels, a total mass penalty > 400 kg will be incurred
- Battery sizing -- 32 Amp-hour sufficient for worst case eclipse; bus can accommodate larger battery.
• Flat panel, trailing bus, conventional solar array technology

• Two-axis articulation, articulate only over polar regions

• Worst-case orbit
  – Beta angle = 0°
  – Eclipse duration = 35 minutes

• Description of operation
  – Assume conventional stowage and deployment methods
  – Over polar regions, solar array rotates about the x-axis (velocity vector) and y-axis to preposition into fixed orientation for optimal power generation during subsequent pole-to-pole pass.
  – Array off-sun angle reaches 0 degrees as vehicle passes over equator and is near 70 degrees while vehicle is over polar regions.

• Solar Array capability (raw) meets end of life requirements with 25% margin using two solar panels, each of which is significantly smaller than the size of the solar panels considered for the NPOES Preparatory Project (NPP) being built at Ball Aerospace.

• Using conventional solar panels, a mass penalty > 180 kg will be incurred
• Additional gimbal/motor increases mission risk
• Potential data loss during panel rotation.
• Battery sizing -- 32 Amp-hour sufficient for worst case eclipse; bus can accommodate larger battery.
UltraFlex Solar Array
Enabling Light Weight Low Volume Technology

Ideal for LEO, GEO, Interplanetary & Planetary Lander Missions

Performance Features
• Specific performance with 27% TJ cells:
  > 150 W/kg BOL & > 40 kW/m³ BOL
• Ultra-lightweight: < 25% weight of standard arrays
• Extremely low storage volume:
  < 25% volume of standard arrays
• High deployed stiffness & strength:
  > 0.5 Hz demonstrated on Mars '01 Lander
  Tensioned blanket/structure forms shallow umbrella deployed shape
• Flight proven low-shock stowage release
• Qualified stowed packaging system:
  Folded gore segments are sandwiched between foam layers in stowed configuration for launch / re-entry protection of cells
• Motor-driven deployment:
  Staging, unfurling, tensioning & latching operations

Application Benefits
• Extremely lightweight allows reduced launch costs and maximizes S/C payloads to increase mission / science return
• High deployment reliability
• Compact stowage volume enables spacecraft and launch vehicle flexibility
• Low deployed mass moment of inertia and high stiffness minimizes attitude & control system (ACS) impacts
• Flexible substrate improves thermal life cycle survivability for long life LEO/GEO missions
• Inherent serpentine string layout accommodates high voltage application
• IG deployment capable with smaller wings
• Wing sizes up to 15 kW BOL
ATK Ultraflex solar panels are being flown as part of the JPL Phoenix Mars lander mission.
SWOT Solar Array Configuration #4
ATK UltraFlex Technology, Single-Axis Articulation

- Flat panel, trailing bus, ATK UltraFlex solar array technology -- significant mass & MOI reduction
  Heritage: Mars Phoenix, NMP ST-8, & baselined for CEV/orion

- Single-axis articulation, articulate only over polar regions

- Worst-case orbit
  - Beta angle = 0°
  - Eclipse duration = 35 minutes

- Description of operation
  - Compact stowage volume and motor-driven deployment w/ staging, unfurling, tensioning, & latching operations.
  - Over polar regions, solar array rotates about the x-axis (velocity vector) to preposition into fixed orientation for optimal power generation during subsequent pole-to-pole pass.
  - Array off-sun angle reaches 0 degrees as vehicle passes over equator and is near 90 degrees while vehicle is over polar regions.

- Solar Array capability (raw) meets end of life requirements with 25% margin using two solar panels.
- Panel area within Ultraflex capabilities.
- Using conventional solar panel technology, a mass penalty < ~70 kg will be incurred.
- Potential data loss during panel rotation.
- Battery sizing -- 32 Amp-hour sufficient for worst case eclipse; bus can accommodate larger battery.
Spacecraft Bus Accommodates Wide Range of Articulation Rates for SWOT Solar Arrays

• Typical BCP2000 momentum exchange actuators sufficient
  ▪ ICESat & CloudSat RWAs: XX N-m-s & XX N-m
  ▪ QuickBird II RWAs: XX N-m-s & XX N-m

• Solar Array Articulation Analysis Results -- Angular Momentum Exchanged

<table>
<thead>
<tr>
<th>Case</th>
<th>Articulation Type</th>
<th>Articulation Angle</th>
<th>MOI (kg-m²)</th>
<th>Max. Ang. Accel. (deg/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat-panel, Conventional S/A</td>
<td>180° about x-axis</td>
<td>208</td>
<td>0.028</td>
</tr>
<tr>
<td>3</td>
<td>Flat-panel, Conventional S/A</td>
<td>90° about y-axis</td>
<td>781</td>
<td>0.007</td>
</tr>
<tr>
<td>4</td>
<td>Flat-panel, UltraFlex S/A</td>
<td>180° about x-axis</td>
<td>71</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Articulate above latitude (degrees) | 60 | 65 | 70 | 75 | 77
Available articulation time (minutes) | 23.2 | 19.6 | 15.3 | 9.3 | 5.0
Case 1: max. ang. momentum (N-m-s) | OK | OK | OK | OK | OK
Case 3: max. ang. momentum (N-m-s) | OK | OK | OK | OK | NO
Case 4: max. ang. momentum (N-m-s) | OK | OK | OK | OK | OK

Achieving 5-minute data outage produces large angular momentum exchange.

Worst case reorientation scenarios
Summary

- The SWOT power requirements can be achieved using a balanced configuration using present day buses and a feasible extension of current solar panel array technology
  - These requirements are met with minimal impact on the attitude control system, and with minimal systematic errors
- Upcoming Ultraflex solar panel technology looks like a potential candidate to satisfy both power and weight constraints
- The power generation strategy proposed here has concentrated on the Ball BCP 2000 bus, but could probably be adapted to other medium sized buses
- Further analysis is currently underway to further validate these conclusions