Atacama Submillimeter Telescope Design Issues

David Woody
Caltech
Owens Valley Radio Observatory
January 2005
outline

• General discussion
  – Major issues
  – Performance limits
• General approaches
• A design concept
First order decisions

- Collecting area
  - 500 m²
- Shortest wavelength
  - 200 μm ? (15 μm surface RMS)
- Budget
  - $70M ??
- Site
  - Atacama, but where exactly???
Performance Issues

• Imaging quality
  – Pointing
  – Field of view
  – Sidelobes
  – Polarization purity
  – Beam shape (surfaces RMS and aberrations)

• Operating conditions (dome?)
  – Weather
  – Maintenance
  – Instrument packages
  – Solar loading

• Detector performance (loading, Tsys)
  – Blockage
  – Scattering
  – Spillover
What effects performance

• Environment
  – Wind
  – Sun
  – Gravity

• Materials
  – Steel
  – Aluminum
  – CFRP

• Geometry
  – Symmetric
  – Off-axis
  – ?

• Fabrication
Basic limits

- Gravity
- Thermal
- Wind
- Survival
Von Hoerner limits

Fig. 3. Regions of diameter $D$ and wavelength $\lambda$, in which the weight of the structure is defined by different conditions, and the three limits of Fig. 2.
## Material parameters

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>CFRP</th>
<th>Aluminum</th>
<th>Invar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [lb/in³]</td>
<td>0.283</td>
<td>0.061</td>
<td>0.097</td>
<td>0.291</td>
</tr>
<tr>
<td>Modulus [10⁶ lb/in²]</td>
<td>30</td>
<td>17</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>CTE [10⁻⁶/K]</td>
<td>12</td>
<td>0.2</td>
<td>23</td>
<td>1.6</td>
</tr>
<tr>
<td>Y/ρ [10⁸ in]</td>
<td>1.1</td>
<td>2.8</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
FIG. 3. Regions of diameter $D$ and wavelength $\lambda$, in which the weight of the structure is defined by different conditions, and the three limits of Fig. 2.
So we need tricks

• Homology can beat gravity by \(~10\)
• Actuators can beat thermal and gravity if
  – Stable measuring system
  – Stable reference system
• But wind is a major problem
  – First order => pointing errors
    • Pointing reference system or guide stars
  – Higher order distortions are very difficult
=> Dome
Fig. 3. Regions of diameter $D$ and wavelength $\lambda$, in which the weight of the structure is defined by different conditions, and the three limits of Fig. 2.
Dome

+ Decrease wind by 10
+ Better Survival
+ Good working conditions
+ Keep panels and structure dry
+ Less dust!!!

• Thermal?
  – Requires insulation
  – Good air circulation during day when closed
Steel vs. CFRP structure

- Steel structure
  + Well understood
  + Cheap
- Aluminum panels
  + Well understood
  + Cheap

- CFRP structure
  + Excellent CTE
  + Light weight
  - Still requires research
  + CFRP panels
    + Excellent CTE
    + Light weight
    - Still requires research
    - Surface layer problems
Geometry

- **Symmetric**
  - Best surface
  - Best pointing
  - Lowest cost
  - ~2% Feedleg blockage
- **Polarization**
  - Symmetric optics
  - Feedleg scattering
  - Effect of panel gaps

- **Off-axis**
  - Best beam
  - No feedleg blockage
  - Higher cost
  - Homology
- **Polarization**
  - No feedleg scattering
  - Asymmetric optics
  - Effect of panel gaps
Accuators

+ Relaxes homology, may be essential
+ Might help with thermal
+ Easy to adjust surface

- High costs
- Needs research
- No good reference structure available
- Software
- Maintenance
An ALMA concept
A previous CELT concept
Investigate an off-axis design

• Better imaging
• No blockage
• Receivers
  – Large volume with no relay optics
    • (large $A\Omega$ requires huge mirrors)
  – Nasmyth platforms?
Off-axis design
Optics

• 25 m clear aperture
• Disk from 50 m f/d=.4 paraboloid
  – Effective f/d=1
• Compact structure
  – Swept volume 21.5 m radius
  – Tipping structure can rotate 360 deg in elev.
Panels

• Bulk or cast aluminum
  • Machined surface
  • Heavy
  • Proven

• CFRP (CFRP or Al honeycomb)
  • Molded surface
  • Light weight
  • Low CTE
  • Surface unproven

• Electroplated Nickel
  • Replicated surface
  • Light weight
  • Can have optical surface finish or diffuse scattering
  • CTE probably limits size to 1 m² (insulate backside)
Raft concept

- Put 10-20 panels on a subframe
  - Fixed adjusters for the panels
  - Set panels on the raft in lab
- Raft $\sim10\,\text{m}^2$
  - 50 rafts
  - 3 actuators per raft
  - Stiff
    - Small gravity and wind distortions
  - Thermally stable
    - CFRP frame or insulated steel
Surface control

• Keck style edge sensors
  – On thermally stable rafts
• Laser interferometry
  – Many fixed sight lines

• Modulated laser absolute measuring system
  – Few scanning systems
  – Just beyond current state-of-the-art
• Wavefront sensor system
  – IR stars
• Shearing interferometer system
  – CSO has used this very successfully
• Out of focus holography
Drive system

• Critical for fast scanning and pointing

• Bearings
  – Hydrostatic
    • Smooth
    • Low friction
    • Messy
  – Wheels and roller bearings
    • Cheap?
    • Standard
Motors

- Commercial motors and standard gear trains (COTS)
  - Limited bandwidth
  - Torque ripple
  - Gear noise
  - May limit tracking performance
- Commercial motors friction drives
  - Difficult to develop high enough torques
  - Torque ripple
- Direct drive
  - Develop a standard ~2 m diameter on-axis motor
    - Use several identical motor on each axis
  - High bandwidth
  - Very smooth tracking (torque ripple within bandwidth)
  - Expensive
Telescope concept

- Off-axis
- In dome
- Electroplated Nickel panels on CFRP rafts
- Modulated laser metrology
  - (corner reflectors formed into panels)
  + shearing interferometer absolute meas. system
- Hydrostatic bearings
- Modular direct drive motors
- Optics details TBD
<table>
<thead>
<tr>
<th>Case</th>
<th>Path Change</th>
<th>Path Error</th>
<th>Pointing Change</th>
<th>Pointing Error</th>
<th>(\frac{1}{2}) WFE</th>
<th>(\frac{1}{2}) WFE after fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Gravity, zenith</td>
<td>494.0</td>
<td>-2.1</td>
<td>0.5</td>
<td>0.6</td>
<td>15.2</td>
<td>9.5</td>
</tr>
<tr>
<td>2 Gravity, horizon</td>
<td>-11.1</td>
<td>-7.2</td>
<td>9.1</td>
<td>16.2</td>
<td>21.5</td>
<td>7.2</td>
</tr>
<tr>
<td>3 Wind, zen., X-axis</td>
<td>0.0</td>
<td>0.0</td>
<td>0.6</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>4 Wind, zen., Y-axis</td>
<td>0.1</td>
<td>0.0</td>
<td>1.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>5 Wind, hor., X axis</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>6 Wind, hor., Z axis</td>
<td>81.2</td>
<td>3.3</td>
<td>2.7</td>
<td>0.0</td>
<td>3.7</td>
<td>1.2</td>
</tr>
<tr>
<td>7 Temp., zen., uniform 10 C</td>
<td>-348.0</td>
<td>-29.0</td>
<td>0.0</td>
<td>0.3</td>
<td>6.0</td>
<td>0.7</td>
</tr>
<tr>
<td>8 Temp., hor., uniform 10 C</td>
<td>382.0</td>
<td>-15.1</td>
<td>8.3</td>
<td>0.0</td>
<td>6.3</td>
<td>2.0</td>
</tr>
<tr>
<td>9 Temp., hor., dT/dX=1C/m</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.1</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>10 Temp., hor., dT/dY=1C/m</td>
<td>93.3</td>
<td>-4.0</td>
<td>0.7</td>
<td>0.4</td>
<td>5.0</td>
<td>0.5</td>
</tr>
<tr>
<td>11 Temp., hor., T(R)=.2R[m]²</td>
<td>111.0</td>
<td>-3.9</td>
<td>2.2</td>
<td>0.0</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>12 Temp., zen., meas. [Error! Bookmark not defined.]</td>
<td>2.2</td>
<td>0.7</td>
<td>1.1</td>
<td>0.1</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Backing structure</td>
<td>Effective surface error [µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity (ideal)</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity (departure from ideal)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute temperature</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>11.0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel and supports</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute temperature</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aging</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel location in plane</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel adjustment perpendicular to plane</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>14.0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary mirror</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute temperature</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aging</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alignment</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>8.4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface setting (holography)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all contributions</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>10.0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total (rss)</strong></td>
<td><strong>22.1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor</td>
<td>Pointing error [arcsec]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------------------------</td>
<td>-------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity (departure from ideal)</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute temperature</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encoders (24-bit)</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metrology (tiltmeters and gap sensors)</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference structure (bearing slop and friction)</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simple FEA

- Weight
  - Tipping weight 510,000kgm
  - Glass 150,000kgm
- Deflection of 250um p-p
- Remove glass => 176um p-p
- RMS => ~40um
- Improved homology expect => ~20um
Main issues

• Performance
  – Collecting area
  – Surface error
  – Pointing
  – Detector loading/Tsys
    • Scattering
    • Emission
  – Beam
    • Sidelobes
    • Polarization purity

• Cost
  – Design
  – Construction
  – Operations