Atacama Large Millimeter Array
NSB Action item

Committee on Programs & Plans
9 May 2006

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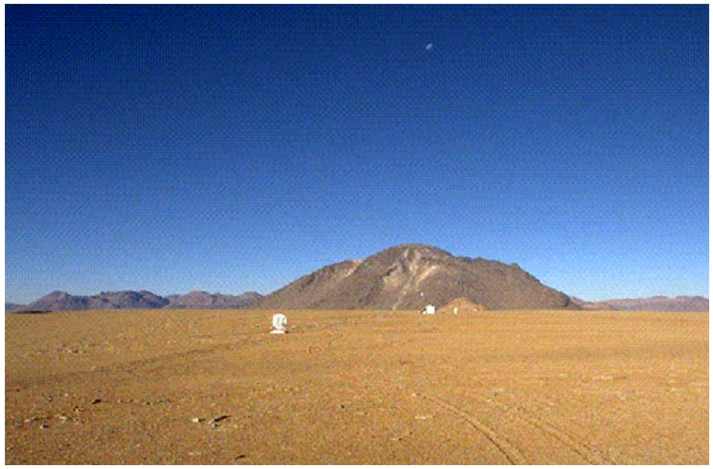
Overview

- Background: The NSB has been kept closely informed of developments in ALMA project (five briefings by AD/MPS since October 2004), focused on cost escalation, partnership issues, and rebaselining of the international project.
- Today:
  - Brief review of project
  - Summarize rebaselining activities and external reviews
  - Update on Director's Review
  - Present rationale and detail for proposed action item
  - Describe follow-up support by MPS and AST
- RESOLVED, that the National Science Board authorizes the Director at his discretion to increase the spending authority for the Atacama Large Millimeter Array under cooperative AST-0223851 and its successor agreements, by an amount not to exceed $176,970,000, and to extend the duration of the award by 24 months through September 30, 2012.

ALMA Project

ALMA is the first global astronomy project

- All three developed regions of the world are participating:
  - Americas: North America (US, Canada + Taiwan) + Chile [Host Country]
  - Europe: through European Southern Observatory (ESO)
  - Asia: (Japan + Taiwan) [Managed outside core bilateral project]
- Partnership emerged from essentially simultaneous decisions that a large imaging millimeter-wave interferometer was very important scientifically -- and worth the investment (100s of $M)
- Capabilities refined by cross-fertilization: a highly-optimized design at a remote and challenging site, constrained by economic realities
- High value science
  - "100-m telescope with Hubble vision"
  - 2 Decadal Surveys in U.S



- Key science capabilities
  - Image proto-planetary disks
  - Image galaxies to z = 10, Milky Way to z = 3

The ALMA Instrument

- **ALMA is an <u>interferometer:</u>**
  - Originally 64 (now proposed as 50) 12m antennas (core bilateral project)
  - Japan's Compact Array: 4 x 12m + 12 x 7m antennas
- **Baselines from 15m to 15km**
- **Sensitive, precision imaging between 30 and 950 GHz**
  - Can accommodate receivers for each atmospheric "window"
  - First light system will have has 6 bands:
    - 100, 230, 345 and 650 GHz (NA + EU)
    - 140, 460 GHz (Japan; + 875 GHz band R&D)
- ***10-100 times more sensitive and 10-100 times better angular resolution compared to current mm/submm telescopes***

Angular Resolution

- $\alpha \sim (\lambda / D)$ (smaller is better)
- Hubble Space Telescope:

  $\alpha \sim 0.1$ arcseconds at 5000Å
- Robert Byrd Radio Telescope at Green Bank:

  100m antenna: at $\lambda = 21$ cm, $\alpha \sim 0.1$ degrees

  Single dish sizes limited by materials

- → Interferometers (Arrays): $\alpha \sim (\lambda /$ separation)

  Multiple antennas needed for collecting area

  Computers essential

  Complex optimization

  35 km separation at $\lambda = 21$ cm, $\alpha \sim 1$ arcsecond
- ALMA

  At 15 km separation, $\lambda = 0.35$mm, $\alpha \sim 0.01$ arcsecond

Interferometry: Costs and Caveats

- No free lunch -- one pays a price for interferometric resolution -- and this is relevant to selecting the final number of antennas:
- *All* interferometric images are reconstructed estimates of the image one would have seen had one mapped the field with a filled-aperture telescope
- Because the aperture of an interferometer is not filled:
  - The edges of the individual antennas produce diffraction artifacts in the images which must be corrected for (next slide) *
  - the total intensity level of any reconstructed image is totally unknown unless it is separately measured, i.e., uniform or slowly varying brightness components across the field are “resolved out” *, **
  - For regions of the sky larger than ~(λ / D), special “mosaic” techniques must be used to estimate and restore the resolved-out intensities (this will be the case for most Galactic sources and some extragalactic ones) *, **

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* The large number of ALMA antennas reduces magnitude of this effect

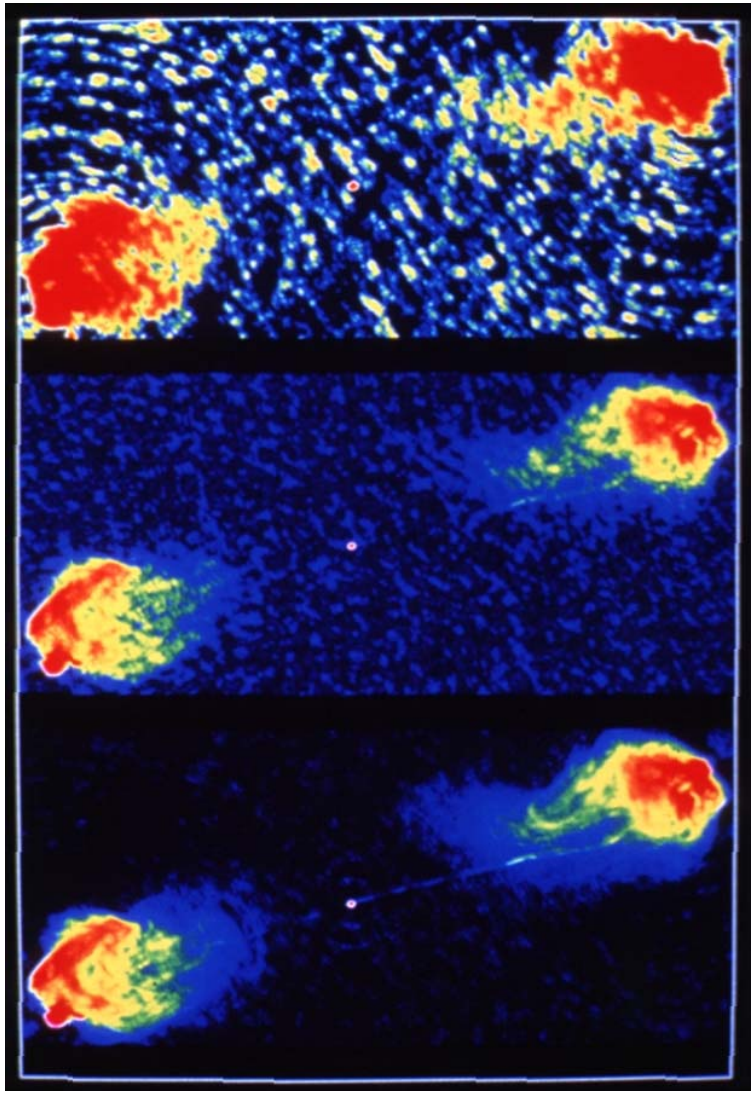
** The ALMA Compact Array is specially designed to assist with this

Image Processing (VLA)

Raw Map

“Clean” Map

“Self-calibrated” Map



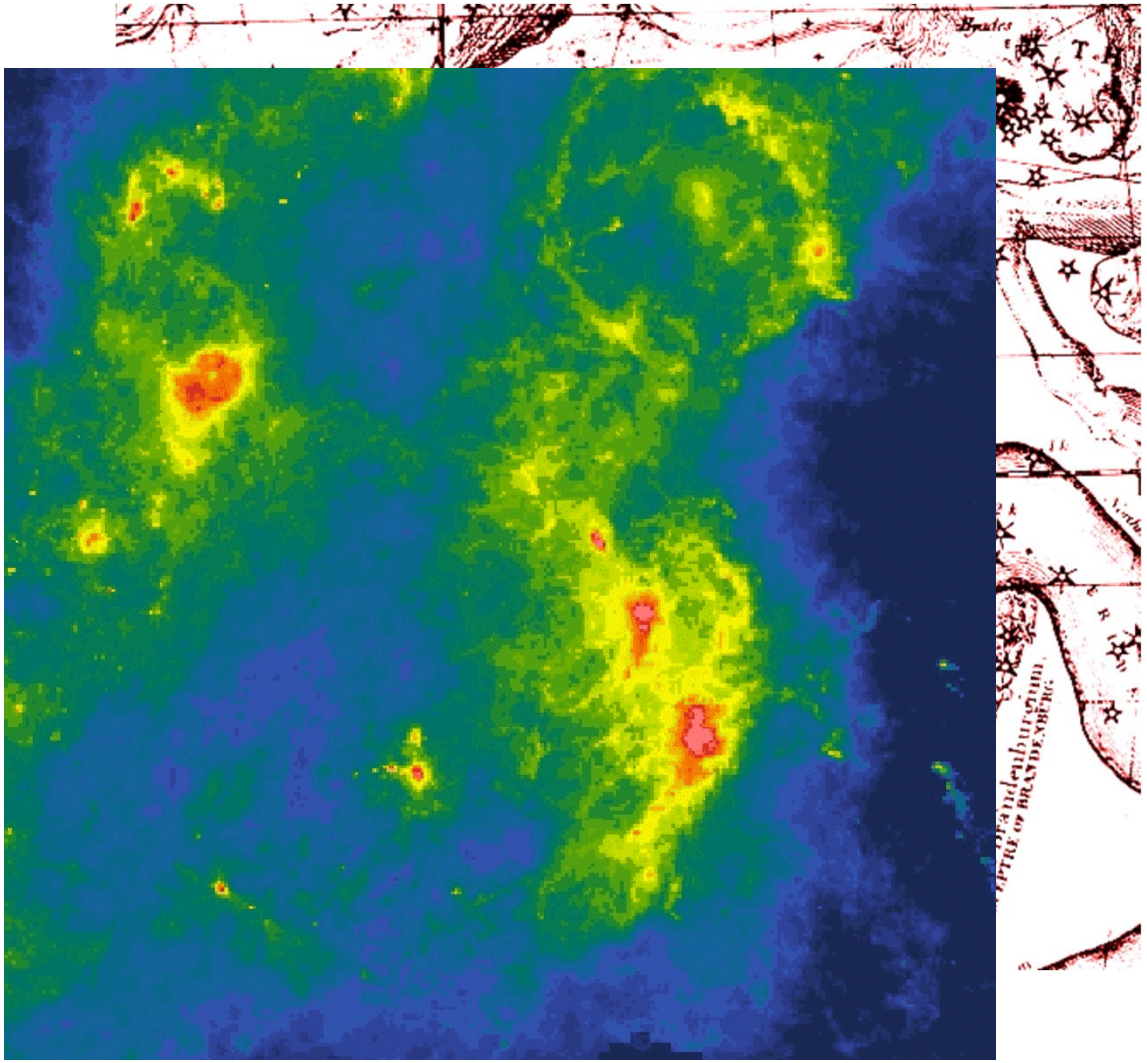
Introduction to ALMA Science

- The 19th century had its own “dark matter” problem: It led to the discovery of the interstellar medium (ISM)
- Long-exposure photography revealed “Holes in the Heavens”
- ISM within galaxies:
  - Ionized (near young, hot stars) → glows → optical spectra

    ALMA continuum + spectroscopy
  - Warm (~ 100K), diffuse: Atomic hydrogen (21cm radio)
  - Cold (~10K) dense: H → H_2 (no ground-based lines)
    - Dust obscuration is proxy for mass **ALMA continuum**
    - Trace molecular species – like CO, CH_3OH – are also proxies for the H_2 but also provide kinematics + chemical composition

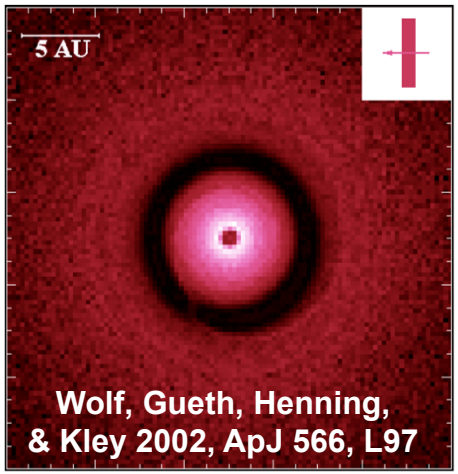
      ALMA spectroscopy

What Does ALMA See?

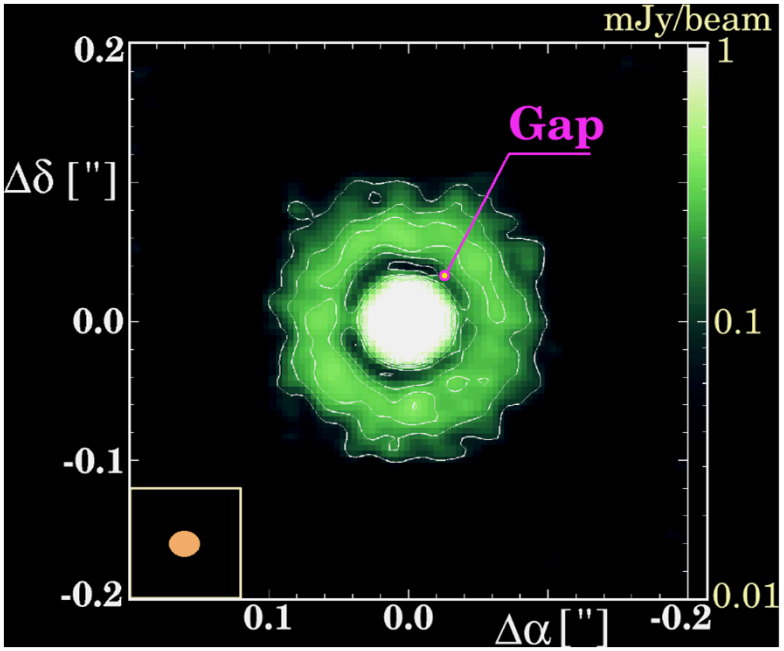


Science Goals:
Imaging Proto-planetary Disks

- Proto-planetary Disk at 140 pc
  - Model of Jupiter mass protoplanet in orbit at 5 AU, within dust disk



- Simulated ALMA Data
  - 428GHz continuum
  - Bandwidth 8 GHz
  - Total integration time: 4 hr
  - Maximum baseline: 10 km
  - Simulated observations at 850 GHz reveal the protoplanet itself



Science Goals: Extragalactic Astronomy
Hubble Deep Field

Deep Surveys

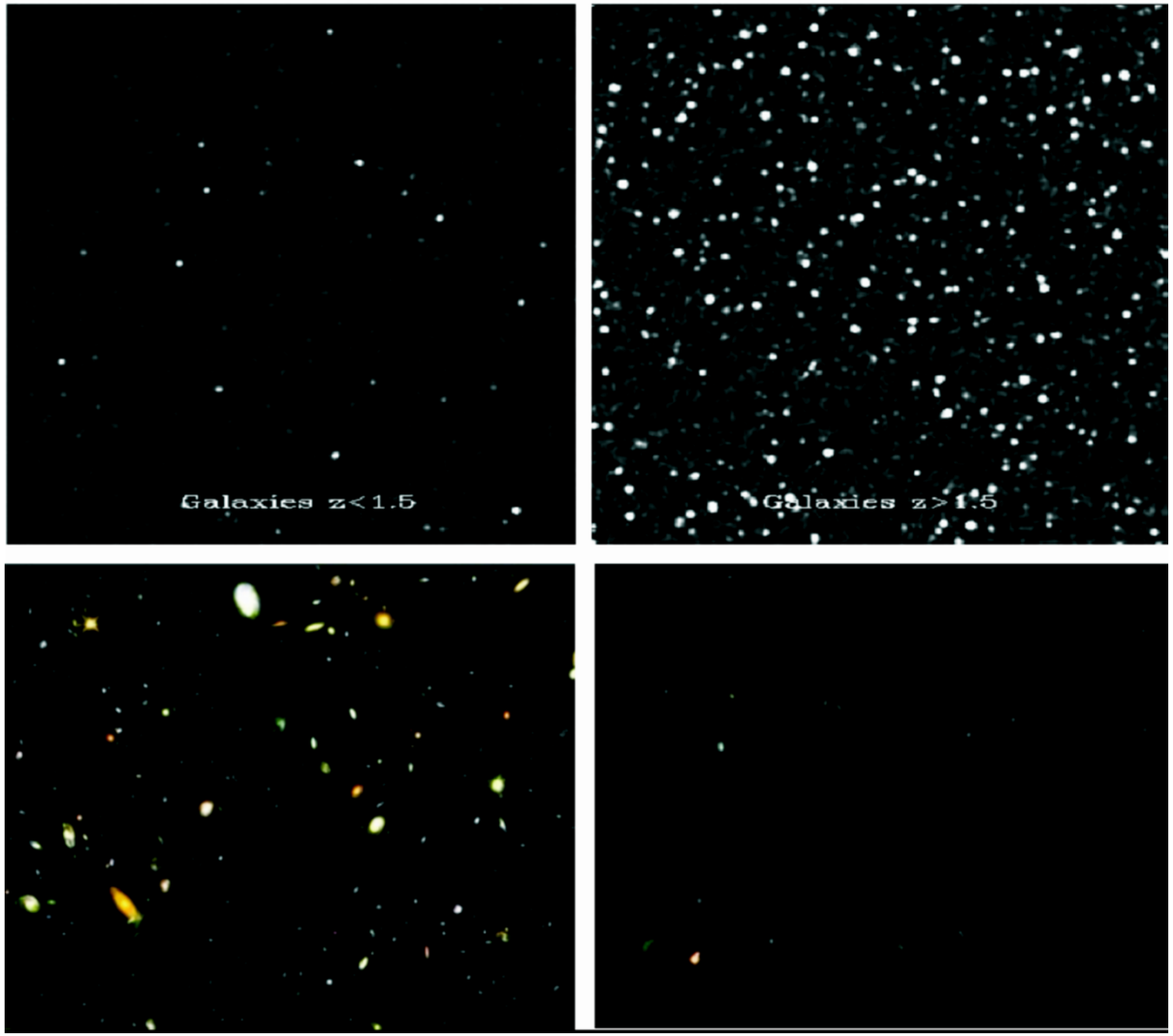
ALMA

Comparable resolution,

but much deeper view

of the early Universe

Hubble Deep Field



Rebaselining

- Why:
  - Partnerships evolved substantially after construction initiated by Congress
  - Partnership complexity -- and cost -- were underestimated
  - Antennas much more expensive than estimated by project and vendors
  - Period of rapid increase in commodity prices (and costs in Chile)
  - Contingency stretched, clearly inadequate -- restore
- When:
  - Began late 2004, new baseline(s) delivered to ALMA Board September 2005
- What -- the Results:
  - Antenna number must be reduced
  - Cost for 50-element array has grown by about 40% relative to original ($344M to $478M); contingency is rebuilt to %18 of cost to complete
  - Maintain parity of deliverable work between NA and EU; new, previously-omitted scope divided equally
  - Schedule to complete 50-element array is not heavily impacted (because of reduced antenna number): U.S. completes in 2011, not 2010
  - List of cost savings proposed to ALMA Board; subsequently approved
  - Early science slips
  - U.S. share of a 40-antenna array would save around $43M

Four Reviews of New Baseline

I. National Academy CAA + ASAC scope studies:

-- Can N_{ANT} be reduced below 64 and maintain the science?

II. ALMA Board review + delta review: "Beckwith Panel

III. NSF review of North American project: "Hartill Panel"

IV. NSF Director's Review (internal): Synthesis of previous reviews and decision on whether to proceed with ALMA

II & III: Complementary reviews with similar core charges:

- Validate proposed new project baseline for construction and operations as a precondition for assessing whether the project should be continued;
- Help determine the correct scope and cost of the rebaselined project;
- Provide confidence that the project rests on a sound organizational basis;
- Provided confidence that the proposed budget and schedule to complete are sound and that both have adequate contingency;
- Assess whether ALMA is appropriately staffed to carry out construction and transition to operations.

Beckwith and Hartill Panel Reviews

- ALMA is technically ready and remains exceptionally promising; no obvious technical show-stoppers
- Can be built to stated costs
- New baseline is complete, correctly costed, with appropriate contingency (see below)
- Management structure and oversight is robust (complexity necessary) and working well; must continue to do so to complete on cost and schedule.
- ALMA Board must continue stepping up to ownership of project – it is the only entity that can do so.
- Critical to manage schedule -- no slippage
- Operations plan is mature but should be pushed (est. $35M per year for NSF) [In process]
- Contingency:
  - Beckwith panel assessed as adequate
  - Hartill panel: >25% of cost to complete is required at this stage. Should be possible to free up, but it might be prudent to also add some additional contingency to cover risks not adequately addressed in methodology (notably from partnership, complexity of global politics) [Under review]

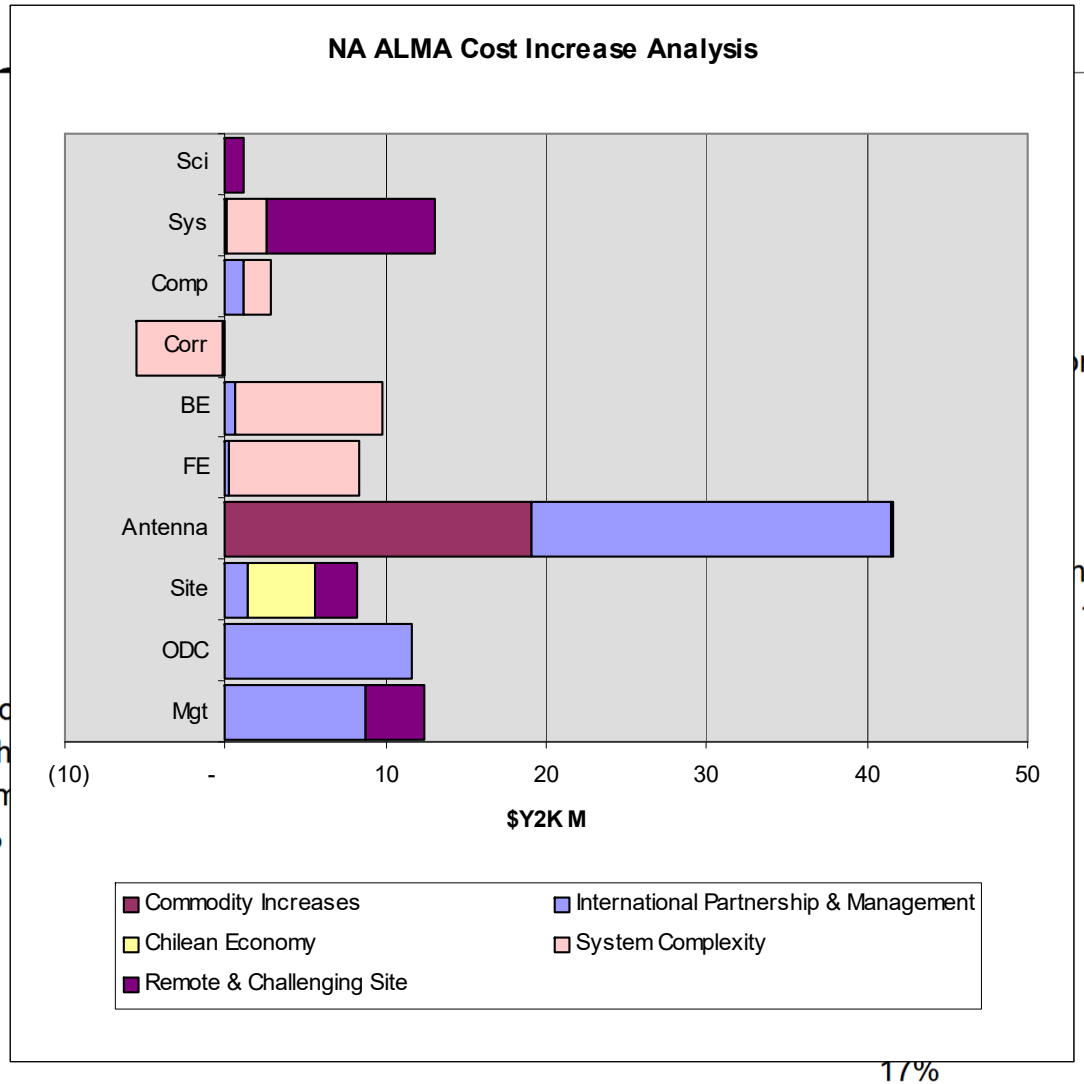
Director's Review -- Background

- Cost containment had continued since delivery of new baseline to ALMA Board:
  - Careful scrubbing: ~$20M(/2) savings
  - Downstream cost of two different antennas to the construction and operations projects was small: <$8M(/2)
- NSF now close to adding Taiwan as a new NA partner: $3M+ per year, extending into operations; can save ~ $20M in MREFC costs
- ESO antenna contract signed --> Largest single budget item now resolved
- Chilean labor issue resolved
- "Rebaselining" completed.
  - Reviewed and verified by external reviews
  - Underlying causes of cost escalation identified and addressed
    - Commodities prices; complexity of ALMA partnership; unidentified scope
  - "Technically ready and scientifically compelling"; "No unidentified scope"

Director's Review

The recommended increase in project cost is large, both in absolute dollars and as a percentage. However, I am now convinced that the increase is necessary and will be well spent on truly transformational science. Further, I am confident that the project can move to completion on the new schedule and budget with the funding profile shown below, and that proper oversight is in place both within the project and at NSF.

Rebaselined Cost and Schedule: 50-element ALMA



Proposed Revised Budget

	FY 2006 & earlier	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	Total
Current budget profile	190.97	47.89	47.07	37.37	20.98	0.00	0.00	**344.28**
Additional NSF funds requested to complete ALMA	0.00	17.38	55.00	36.38	21.78	21.44	3.00	**154.98**
Total MREFC Funds	**190.97**	**65.27**	**102.07**	**73.75**	**42.76**	**21.44**	**3.00**	**499.26**
Pass-through authority for Canada and Japan	9.64	4.78	3.71	2.19	1.13	0.53	0.00	**21.99**
Requested additional spending authority	9.64	22.16	58.71	38.57	22.91	21.97	3.00	**176.97**
Total requested spending authority	**200.61**	**70.05**	**105.78**	**75.94**	**43.89**	**21.97**	**3.00**	**521.25**
TOTAL MREFC funding profile	***190.97***	***65.27***	***102.07***	***73.75***	***42.76***	***21.44***	***3.00***	***499.26***

- Recognized this will have a serious impact on downstream MREFC projects, but action is necessary to continue to maintain U.S. interests in and access to, this transformational global project
- FY 2007 and 2008 are recognized as special challenges
- If proposed action is approved by NSB, will immediately initiate contacts with OMB, OSTP, and Congress to alert them to proposed changes in MREFC account

MPS Activities

- If proposed action is approved by the NSB, MPS will…

Recommendation

I recommend that the Board approve the proposed changes to the ALMA project in accordance with the following resolution:

<u>RESOLVED</u>, that the National Science Board authorizes the Director at his discretion to increase the spending authority for the Atacama Large Millimeter Array under cooperative AST-0223851 and its successor agreements, by an amount not to exceed $176,970,000, and to extend the duration of the award by 24 months through September 30, 2012.

Arden L. Bement, Jr.

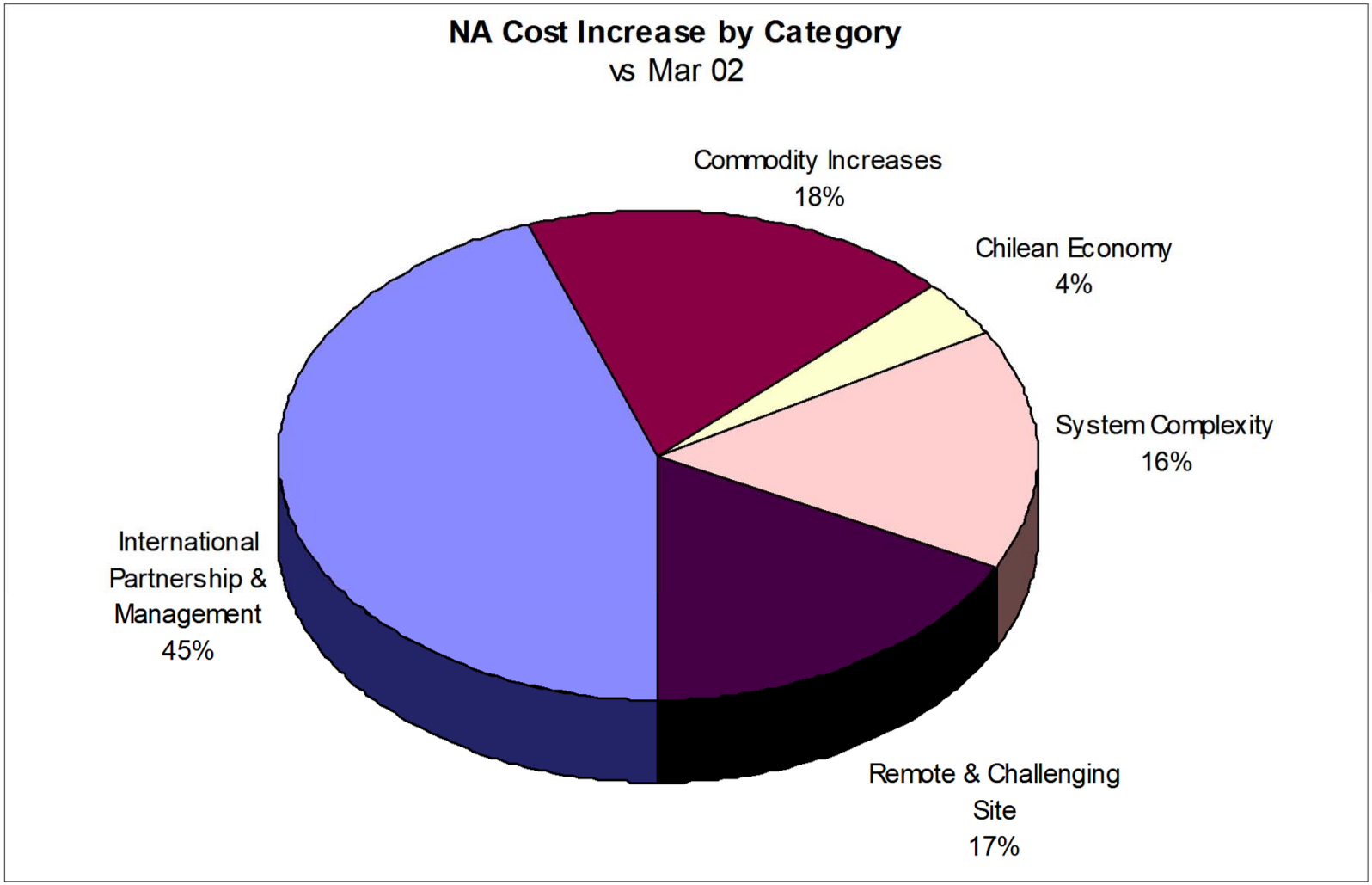
Director

BACK UP SLIDES

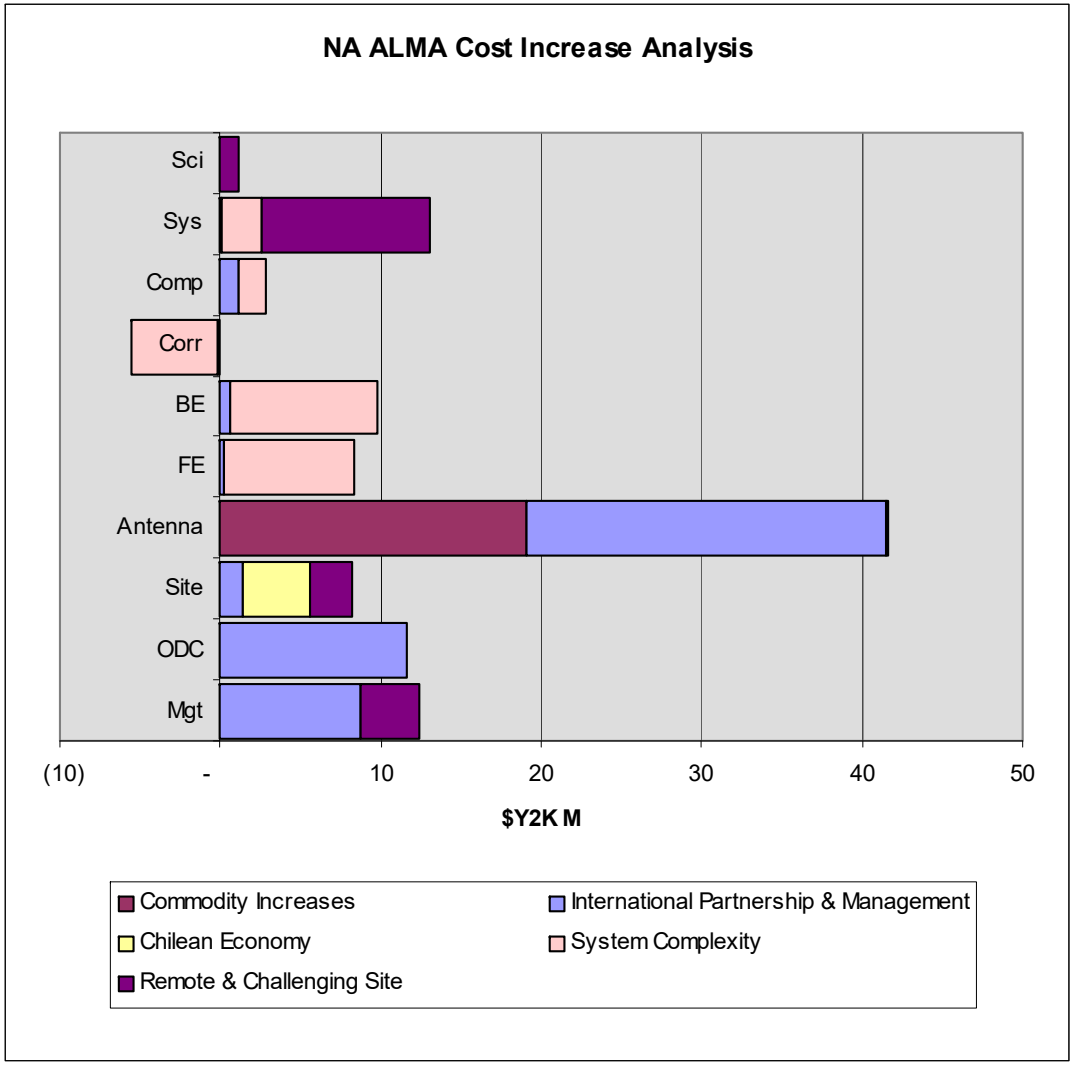
Why 50 Antennas?

- Cost/benefit/risk is the core issue
- Cost savings to U.S. is ~$43M in going from 25 to 20 antennas
- Places ALMA science at risk
  - Cartoon-level metrics show a soft roll-off of array capabilities; ALMA will in fact recover some lost capabilities at highest frequencies because the production antennas and receivers in the highest bands will significantly exceed specifications; however, there will be no recovery at lower frequencies
  - Not easy to extend the metrics to more sophisticated levels -- there is no direct experience at ALMA's large baselines and high frequencies -- but:
    - Baseline redundancy (β) becomes increasingly critical as atmospheric effects become progressively more important (long baselines+ high frequencies); $\beta \sim N_{ANT}^2$
    - CAA drew a floor at $N_{ANT} = 40$ but this is the operating number; ALMA will move 1-2 antennas per day and can expect some number out of service
    - Science is imperiled at $N_{ANT} = 40$, and meets the CAA floor at N_{ANT} ~43, but the savings are reduced from $43M to $17M.
    - Original science is within reach with a 50-element baseline
    - Japanese ACA is not a realistic alternative recovery path
      - Different antenna specs
      - Generally committed to important complementary mission
      - Cost to gain this capability (under study)
- Partnership weakened, U.S. marginalized
  - ESO has already decided on a 25-antenna contract
  - Buying 20 antennas makes U.S. minority partner
- Cannot change our mind later: Can't re-open assembly line

Cost Escalation by Category



Cost Escalation by IPT



Some ALMA Milestones: 2003-2005

- U.S. construction begins (2/02)
- Signature of ALMA Agreement and start of bilateral construction (2/03)
- ESO construction begins (1/03)
- Staffing of Joint ALMA Office (2003-2004; continuing)
- Groundbreaking on Chilean site (11/03)
- Japan joins expanded partnership (9/04)
- All Chilean agreements completed (12/04)
- U.S. antenna contract signed (7/05)
- ESO antenna contract signed (12/05)
- ESO antenna transporter contract signed (12/05)

Optical and Radio Telescopes

- Angular resolution: $\alpha \sim (\lambda / D)$ (smaller is better)
- Optical Telescopes:
  - Geometric optics
  - Focal plane large
  - Angular resolution ("detail") limited by atmospheric distortion, not diffraction (except for HST and AO systems)
  - Field diameter/Resolution ~ 5000
- Radio Telescopes:
  - Physical optics
  - Small focal plane (single on-axis pixel spot is typical)
  - Angular resolution determined by physical size of antenna
  - Field diameter/Resolution < a few
  - Resolution limited by physical limitations of structures…**BUT**

Antenna Scope Reviews

NRC/CAA Descope Study Charge sent in February 2005, anticipating possible reduction in N_{ANT} to the range 36-56

- Requested assessment of:
  - Impact on Level-I ALMA science goals
  - Loss in speed, imaging, sensitivity, mosaicing quality
  - Whether descope ALMA would still be transformational
  - Whether hard cliff exists in performance *vs.* N_{ANT}
- Completed[1] May 2005
  - Two of the 3 Level-I requirements are missed in any descope from 64 to 50 or 40 antennas
  - 40 or 50 element array is still transformational
  - Below 40 antennas, community support would be greatly imperiled
- [1] "*The Atacama Large Millimeter Array (ALMA): Implications of a Potential Descope*"

ASAC Reviewed Same Issue in 2005:

- Reduction to N = 50 is still transformational but level I requirements are in jeopardy within stipulated time limits
- At N = 40 loss of baseline redundancy begins to be especially worrisome, particularly at high frequencies and long baselines

Four Reviews of New Baseline: Beckwith Panel Review – I

ALMA Board Review of New Baseline: ("Beckwith Panel")

- Review of full international project; presentations led by JAO
- 4-day review (plenary + break-out sessions): October 13-16, 2005
- Operations included
- Single antenna design still assumed
  - "Delta" review needed
  - Delta impact found to be relatively small
- Main Conclusions:
  - The committee believes ALMA can be built to the current cost estimate… providing that the execution of the program is robust at all levels of the project
  - The science capability of ALMA remains compelling…[and] ALMA's technical readiness level is high
  - The detailed project plan is realistic
  - The estimated operations costs appear to be adequate and not excessive
  - Possible advantages with two antenna designs

Four Reviews of New Baseline: Beckwith Panel Review – II

Three main concerns identified:

- Schedule: "Poor schedule discipline and delays in antenna integration could increase overall project cost"
- "Delays in early implementation of an operations plan together with delays in funding to begin work on some elements of operations could increase the long-term costs of the project." (See below)
- Board oversight: "The Board must act expeditiously and effectively to enable the project to stay within its current cost estimate" (Addressed immediately by Board – next slide)
- Local Labor: "[The] lack of a plan to hire staff in Chile, an area with potential risk for cost growth" (This issue retired)

ALMA Board

- Need for transition to mature board
  - Timely decision-making
  - Ownership of project
  - Institute clear processes for expedited decision making
  - Robust mechanisms for oversight of full project
  - Improved support for information flow to, & decision-making by, Board
    - JAO must staff the Board in a much more structured way
    - Bolster JAO staffing as necessary
- Working Group → Implementation Plan
  - Dual Executive appointments for JAO
  - Personnel Committee
  - Finance Committee
  - More: AMAC, revisions to Agreement

Four Reviews of New Baseline: Hartill Panel Review of NA ALMA – I

IV. NSF review of NA project and proposed new baseline: ("Hartill Panel")

- Why another review? NSF funding goes to ALMA NA, not to the international project. Specifically:
  - Further "drill-down" into sample elements of the WBS in order to validate the comprehensiveness of the new baseline
  - Specifically assess the adequacy of North America's total cost, schedule, and funding profile;
  - Assess the project's – and especially North America's – contingency, especially in light of the different approaches historically used by the US and by organizations such as CERN and ESO;
  - Evaluate North American project management and AUI's oversight thereof.
- 3-day review January 30-February 1, 2006
- Review of North American ALMA, led by NRAO/AUI
- Operations included

Four Reviews of New Baseline: NSF Review of NA ALMA – II

Main Conclusions:

- "Panel recommends that the National Science Foundation go forward with [this] project"
- "The technical readiness of the project is very high and construction is under way"
- "The new management of the North American part of the ALMA project appears to be functioning well"
- "The construction cost growth of the ALMA project is understood and is detailed in the management section of the report"
- "[The]… project organized, staffed, committed, and positioned to complete the ALMA NA project within the proposed new baseline"
- "[P]roject costs are understood and…the schedule while tight can be met with careful management…"
- "The [ALMA] management structure that is in place gives confidence that the needed performance level will be met. The…structure is working well and must continue to do so in order to deliver the project on cost and schedule"
- "[T]his Panel judges the proposed new baseline cost estimate to be sound and appropriate for this stage of the project total project cost"

Four Reviews of New Baseline: NSF Review of NA ALMA – III

Main Concerns:

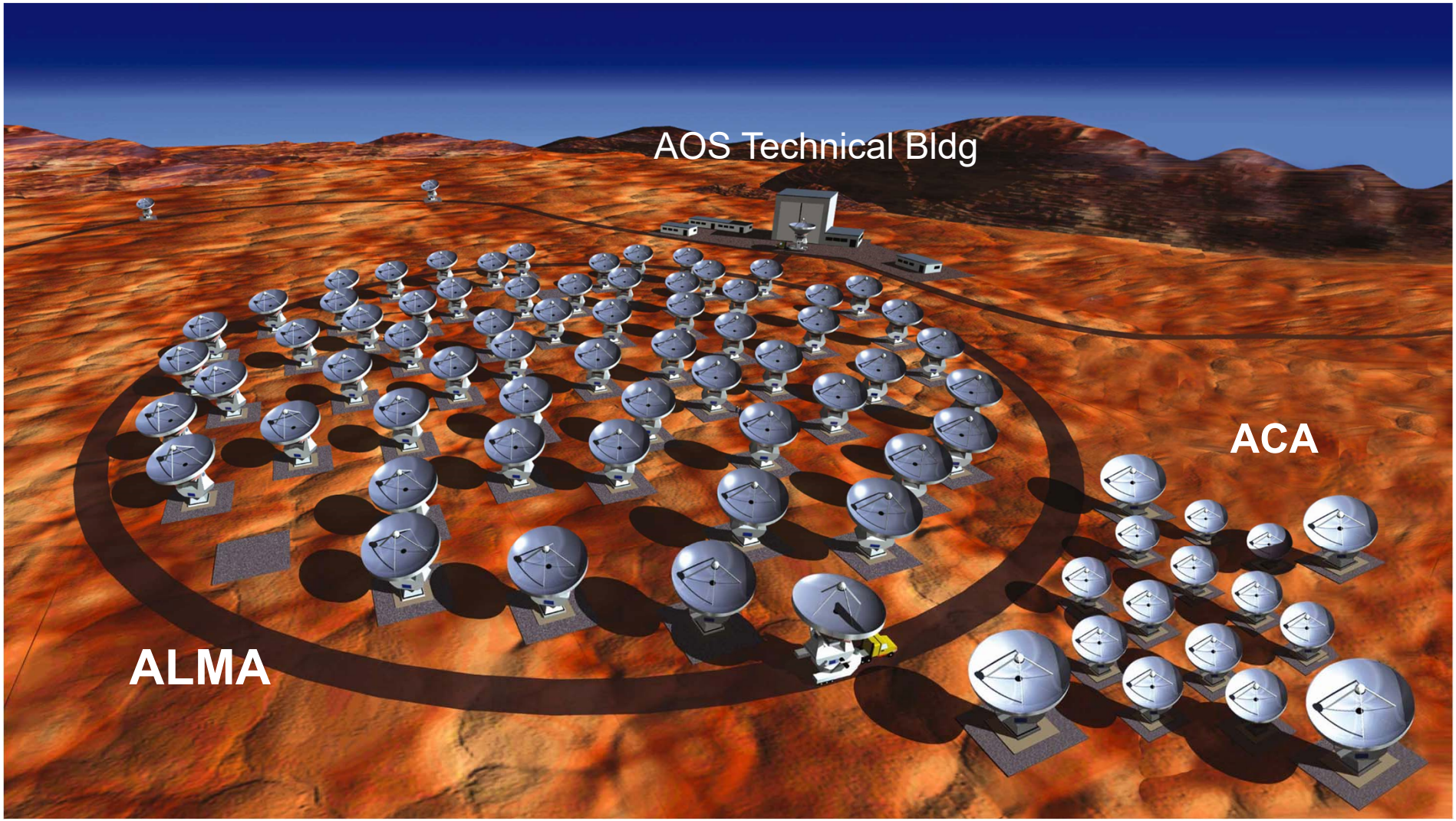
- Schedule (cf. Beckwith panel)
  - Frequent reviews
  - Improved interfaces to ESO project
- Contingency partitioning
  - Centralize IPT budgets
  - Increase cost and schedule contingency (?)
  - Use Taiwan
- PMCS – must be fully operational
  - NA now operating
  - ESO will be late

Four Reviews of New Baseline: NSF Review of NA ALMA – IV

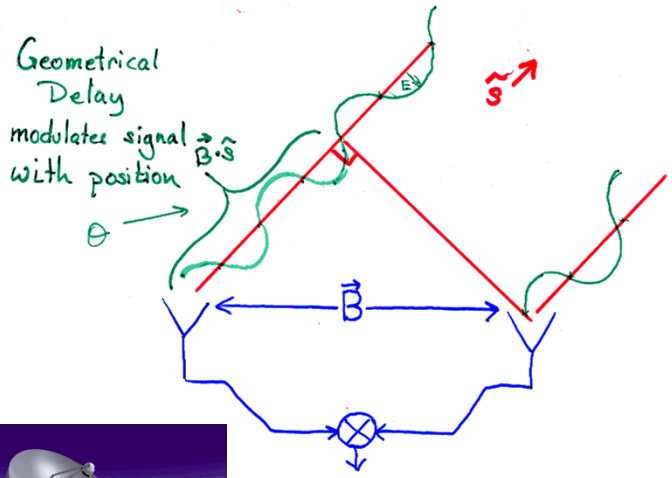
Main Concerns (continued):

- Antenna contract – management, oversight, schedule, change orders all noted, but:
  - "[The] risks of North American antenna procurement are acceptably low for a contract of this size and technical complexity"
  - Apex performance gives "…assurance that the design is sound"
  - "Vendor risk is minimal"
  - "…[C]ontract… contains no undue risks"
- Nevertheless, will ask AUI:
  - Mentor NRAO antenna PM
  - Strengthen NRAO technical team and process (change order, QA)
  - Strengthen NRAO contract oversight

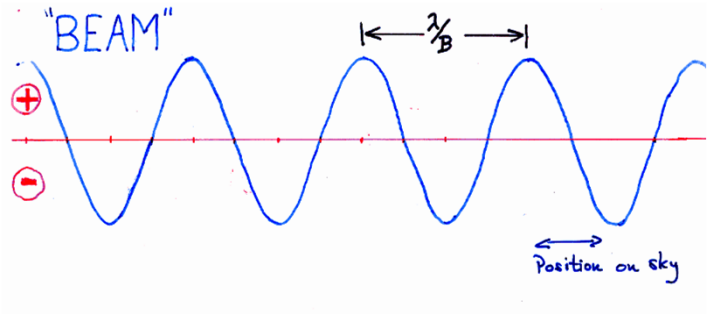
Enhanced ALMA

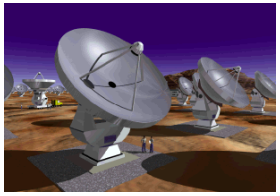


How an Interferometer Sees
(more like human hearing than vision)



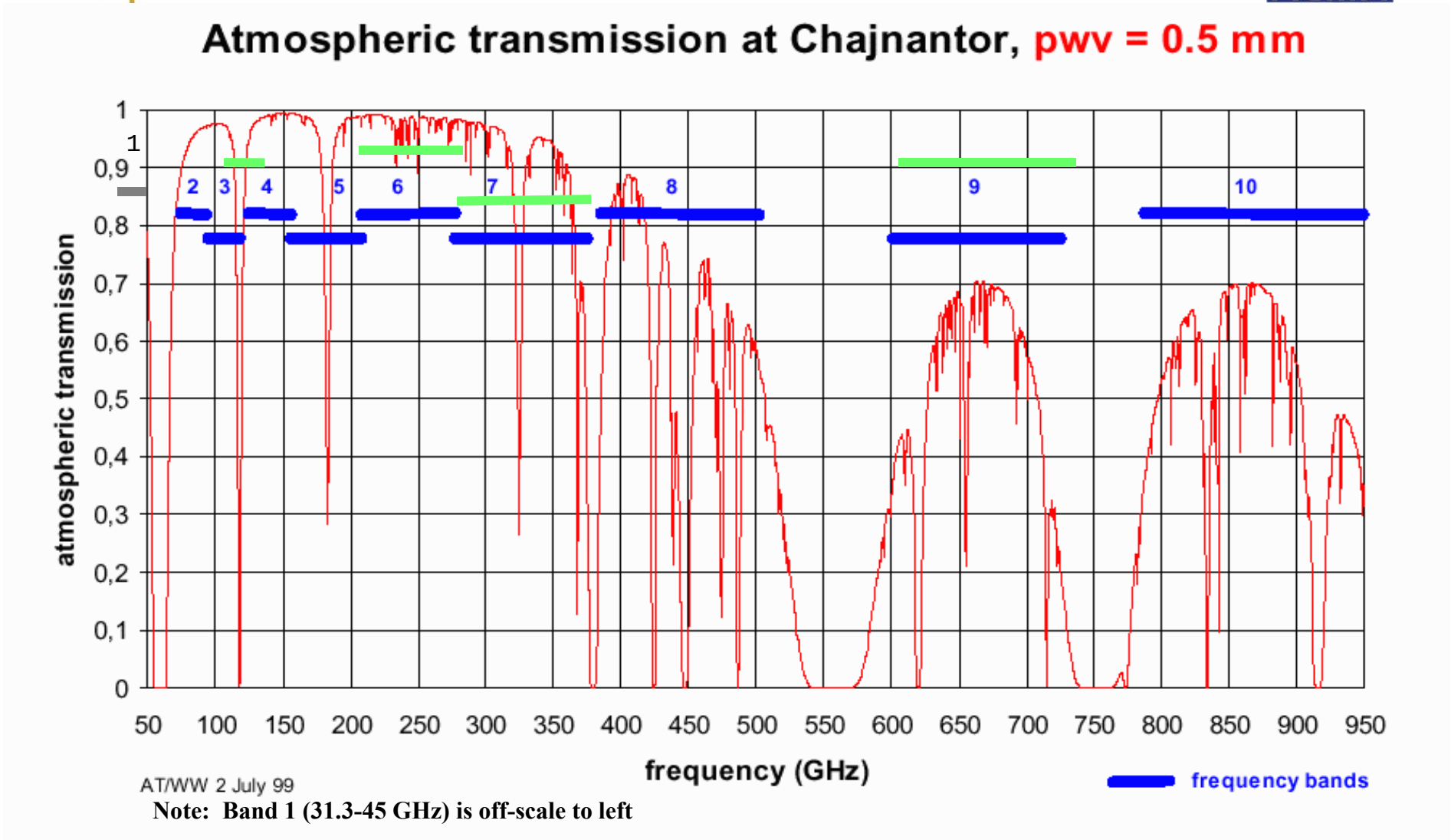
Phase difference
between two antennas
makes sensitivity on sky
a sine-wave





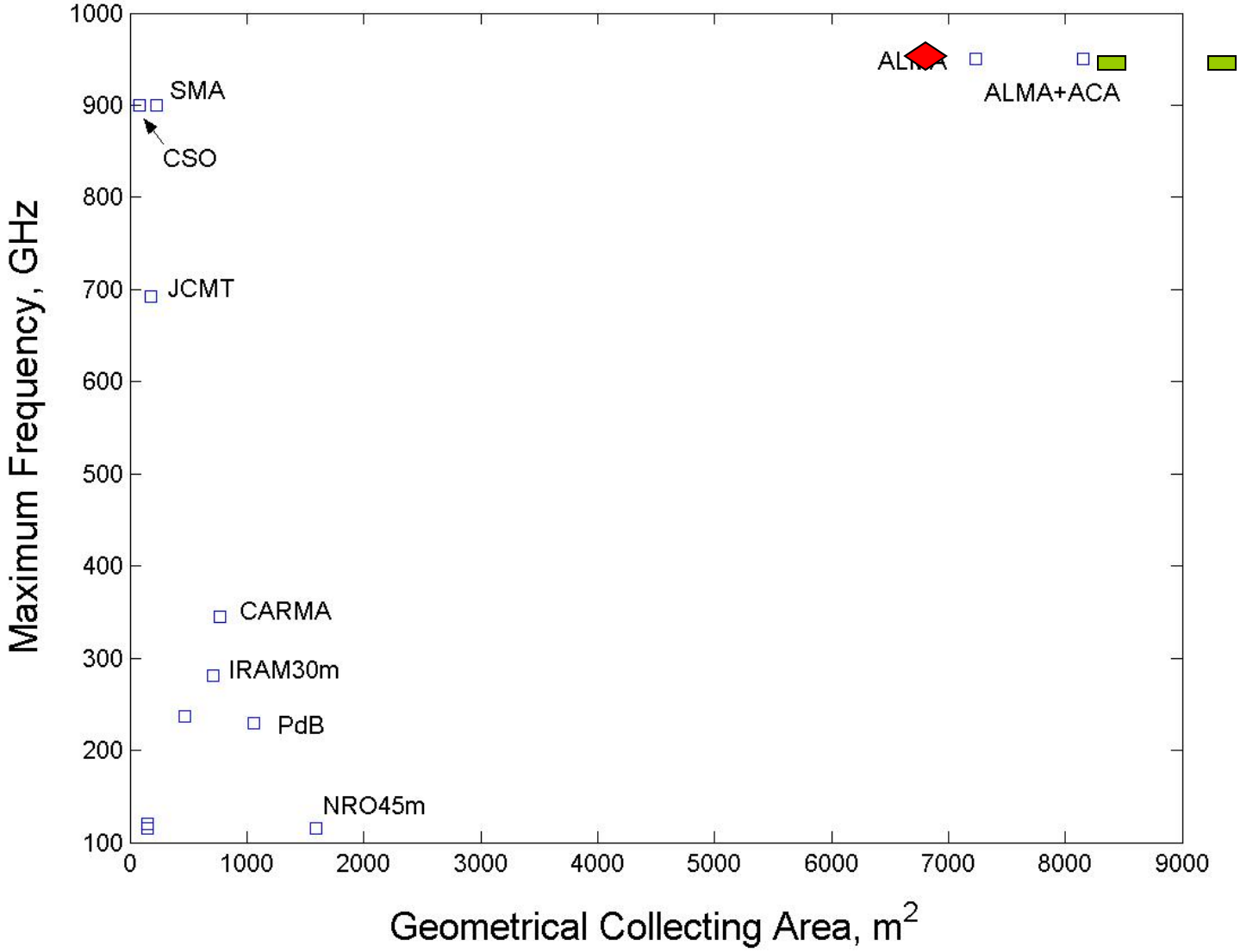
Each Pair of Antennas Measures the
"Wave Content" at a Frequency
Related to their Separation (big
separations measure high frequency)
(Engineers: Interferometer takes
Fourier Transform of Sky)

Frequency Coverage

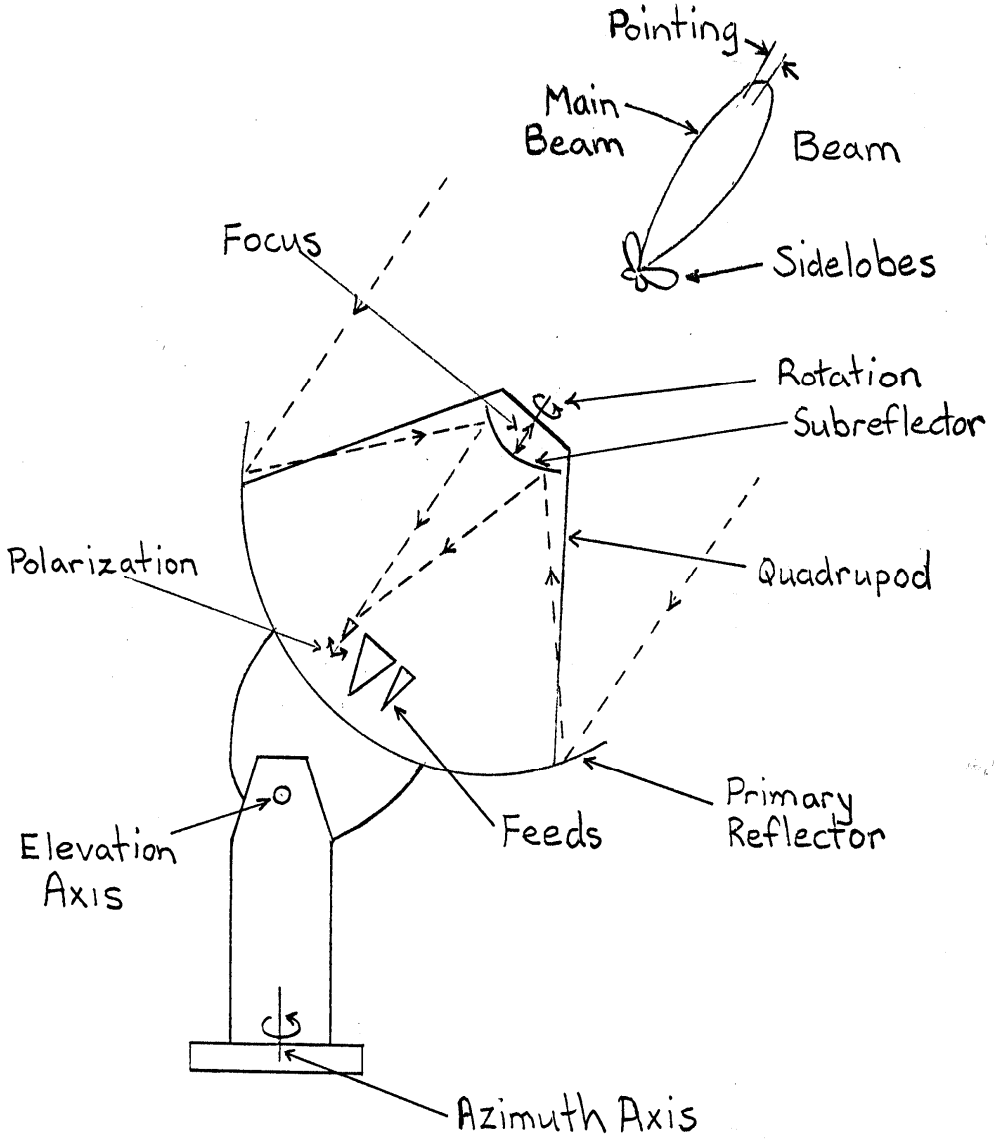


Note: Band 1 (31.3-45 GHz) is off-scale to left

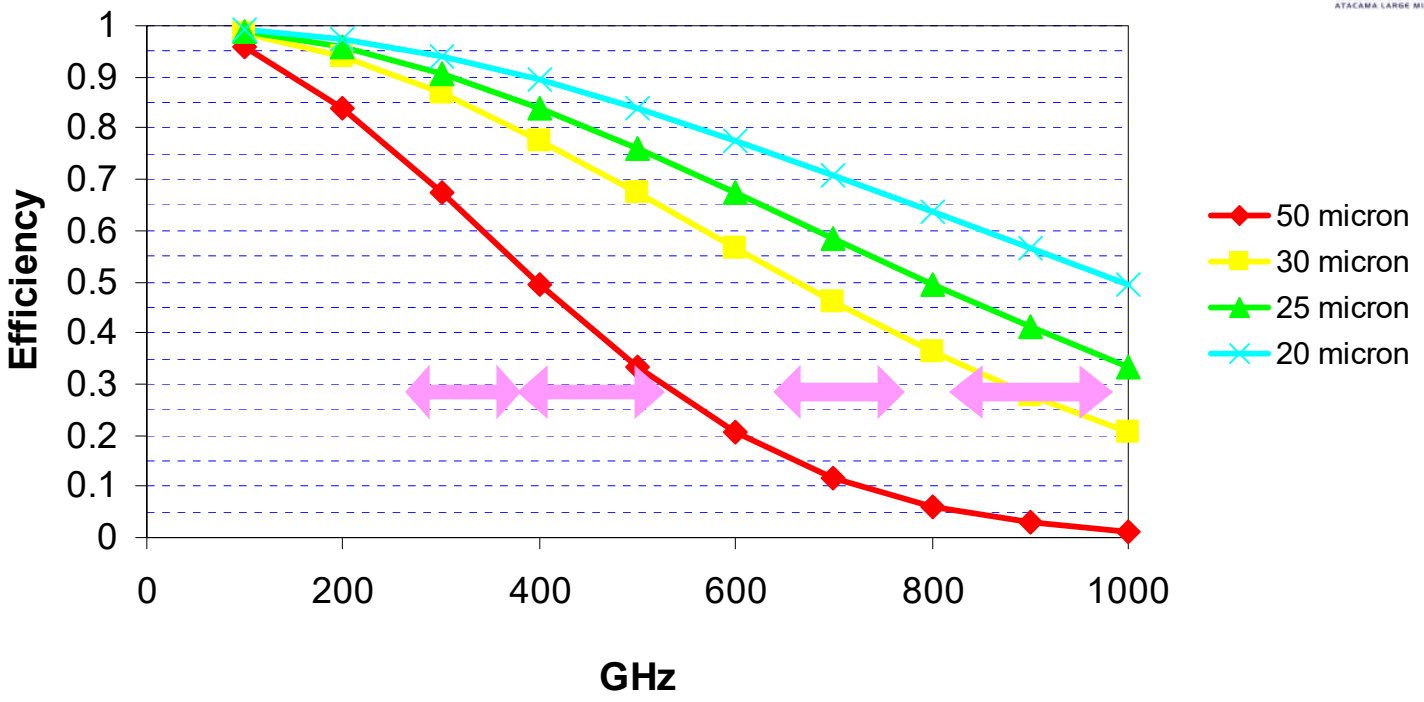
mm and sub-mm Telescopes



Antenna Key Features



Ruze equation



Importance of trade-offs in efficiency vs number of antennas:

Example: At $\nu \sim 1$ THz, surface improvement of 30→25 μm is equivalent to having 50% more antennas

Administrative Issues – Outline

- Summary of recent progress:
  - Antennas
  - Local labor
  - Rebaselining
  - Partnership (with Taiwan)
  - ALMA Management and partnership
- Taiwan
- ALMA Management and partnership
- Reviews and outcomes:
  - Academy CAA study of ALMA scope
  - ALMA Board review by Beckwith panel
  - ALMA Board “delta” review by Beckwith panel
  - NA ALMA review by Hartill panel
- PMCS
- Operations

Recent Progress - I

- Antennas
  - AUI contract for 25-32 units placed in July (no penalty for buying fewer units above 8)
  - ESO contract for 25-32 units placed in December
  - Two different antennas, two different vendors
- Taiwan (details later)
- Local labor: AUI will employ
  - Removes major uncertainty & removes decision from critical path
  - Agreements in process, including amendment to ALMA Agreement (NSF-ESO) and implementing agreement (AUI-ESO)
  - Interim hiring mechanism is in place and being used

Recent Progress – II

- Rebaselining
  - New baseline developed and costed by JAO (September 2005)
  - 4 reviews (described in detail later):
    - National Academy CAA scope study
    - ALMA Board review
    - ALMA Board delta review
    - NSF review of North American ALMA project
- Reductions to mitigate cost increase in new baseline
  - Descope in antenna number from 64
  - Further scrubbing of proposed baseline: ALMA Board action to reduce cost by ~ $22M
  - New partner for NSF: Taiwan
- ALMA management and partnership (details later)
  - Structure
  - Board reform
  - Other mechanisms

Taiwan – I

- Negotiations are in an advanced state for Taiwan to become part of ALMA-NA
- High-level agreement between AIT and TECRO designating NSF and NSC as Executive agencies
- Draft TAPRA Agreement – modeled on NRAO Agreement with Canada
  - Canada grandfathered in for Board seat, *etc.*
- Goal: Both agreements complete by August 2006 (TAPRA terms and language essentially finished)

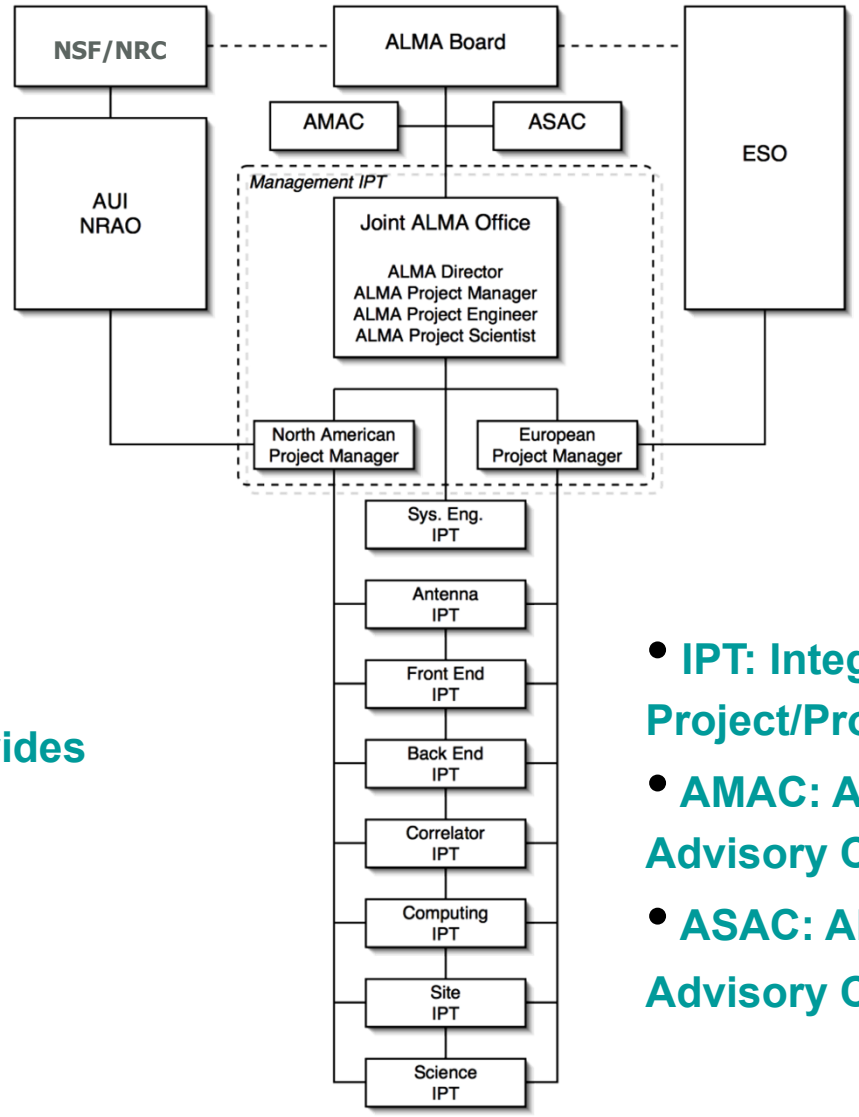
Taiwan – II

- Taiwan will agree to contribute ~ $3M per annum (FY2006) to ALMA for at least ten years
  - May be indexed annually
  - First 7 years will support ALMA construction (~$21M)
  - Will then transition to operations support
  - Contributions required to have no impact on NA schedule or technical risk
  - Best efforts will be made to place up to half of this amount back in Taiwanese industry ($17M already identified by NRAO)
- The cost of any work transfer to Taiwan will include necessary margin/contingency and management overhead; there will be *some* additional costs associated with moving work to Taiwan (TBD)

ALMA Agreement

- Key Elements:
  - Parity
  - Maintain existing institutions (NRAO)
  - Dual Executives
  - Value-based →Deliverables, not cost
  - Binding international agreement – commits USG
- ALMA Board established:
  - "Budget oversight and policy control"
    - Ownership of project
    - Integrated oversight of full project
    - Policy formulation
    - Flesh out skeletal structure outlined in ALMA Agreement
    - Represent national/agency interests
  - 4 members per side (bilateral) + Japan + Chile
  - Rotating Chair, Vice Chair (2 year cycle)
  - Chair, Vice Chair cannot be AUI or ESO employees

Complex International Partnership



- North America: US + Canada (+Taiwan, in process)
- ESO: Spain initially an associate of ESO (joining)
- Dual Executive
- Joint ALMA Office provides central management
- Japan joined in 2004, creating the enhanced ALMA project

- IPT: Integrated Project/Product Team
- AMAC: ALMA Management Advisory Committee
- ASAC: ALMA Science Advisory Committee

PMCS

Has three modules:

- Integrated Project Schedule
  - Live in early 2005
  - Fully operational May, 2005
- COBRA financial system
  - Live August 2005
  - Two slightly different baselines (interim); were to be reconciled after NSF decision on project baseline
- EV Module
  - NA
    - EV live now
    - Differences in 2 baselines produced some questionable results
    - Fully debugged and operational by March 31
  - ESO: EV probably live not till June
  - Have asked JAO to accelerate, but problem is at ESO (new financial system)

Operations – I

- Beckwith panel: "[T]he estimated operations costs appear to be adequate and not excessive."
  - Zero-base review (Bob Williams, Director Emeritus, CTIO)

- Hartill panel: "The operational plans for ALMA are at an early conceptual stage and will need considerably more work before a solid cost estimate can be developed. The initial cost estimates presented to the Panel seemed to be reasonable.

- Essential to move forward…

Operations – II

- Complete operations plan exists
  - Version A accepted in April 2005
  - Version B to be delivered March 2006 – delay due to:
    - Rebaselining
    - Local Labor mechanism with organizational + cost structure (now resolved)
    - Japan must be treated more comprehensively
- Deliver full and NA budget and ramp-up profile once new NSF baseline is adopted
  - Integrate Canada and Taiwan
- AST will peer-review the NA plan in 2006:
  - Structure: International core operations + NAASC increment
  - Elements in NAASC needing review include:
    - R&D
    - Fellowships, Grants proposals

Future Reviews

- Total Project Reviews Owned by ALMA Board
  - Mechanism: AMAC or “ad hoc” Committees (like, Beckwith Committee)
  - Timescale: yearly

- NA Reviews
  - 6-month schedule, with rotating focus and complete project reviews every 12 to 18 months
  - A la Ice Cube, LIGO (we know how to do this)