ALMA Construction: Lessons Learned

Robert Laing (ESO)

ESO ALMA Lessons Learned Review: Scope

- Review lessons learned for future projects from an ESO perspective
  - E-ELT, CTA
- Not a formal review of the entire ALMA Project
  - European ALMA Construction Programme
- Construction, not Operations
- Panel
  - Chaired by Xavier Barcons
  - Reported to ESO Council
  - Main report can be made public
  - a few topics redacted

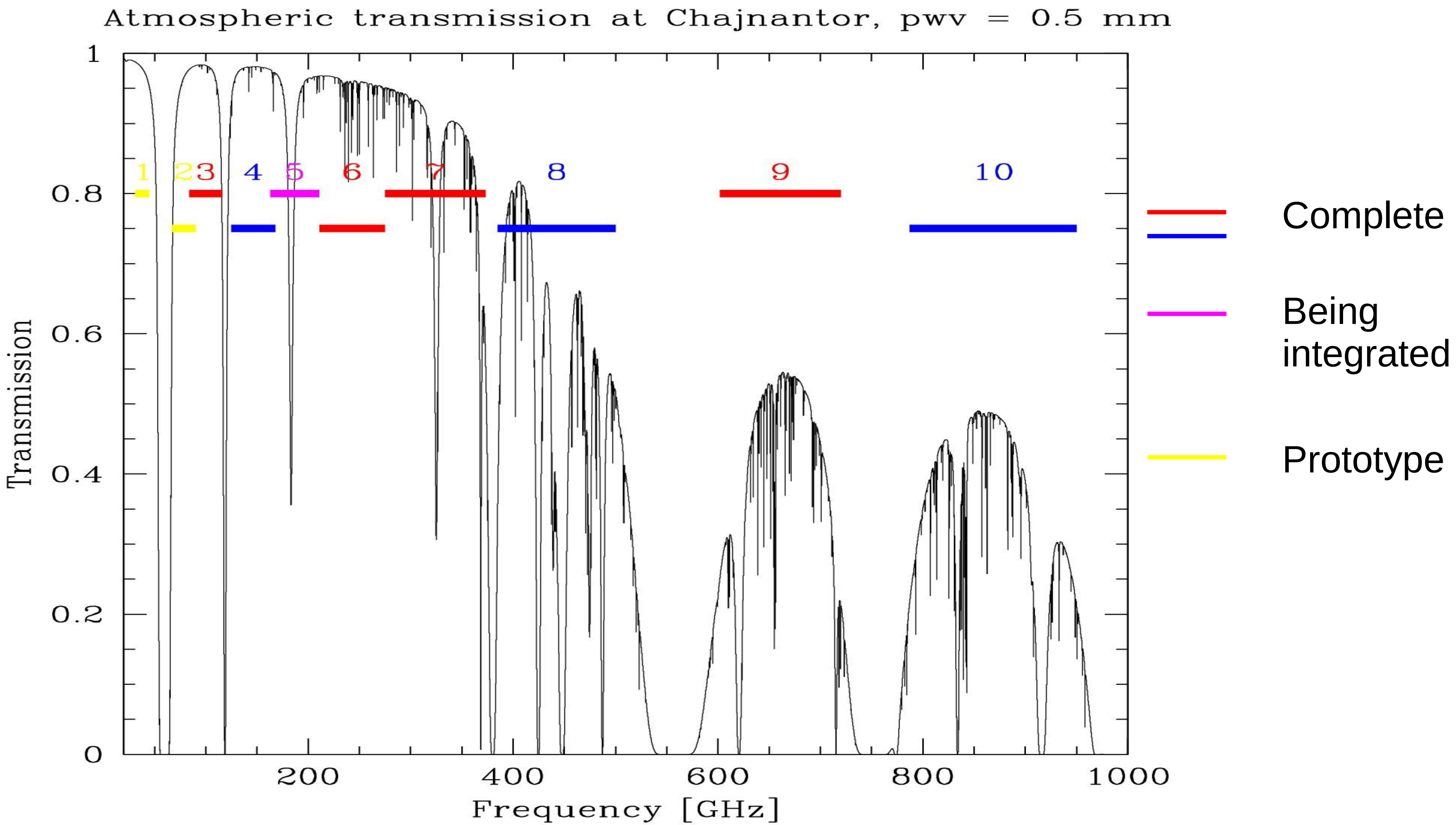
What is ALMA?

- Aperture synthesis array optimised for wavelengths of 1cm – 0.3mm (35 – 950 GHz)
- **High, dry site**, Chajnantor Plateau, Chile (5000m)
- 54 12m + 12 7m antennas
- Baselines from ~15m to 16km.
- **Resolution**/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

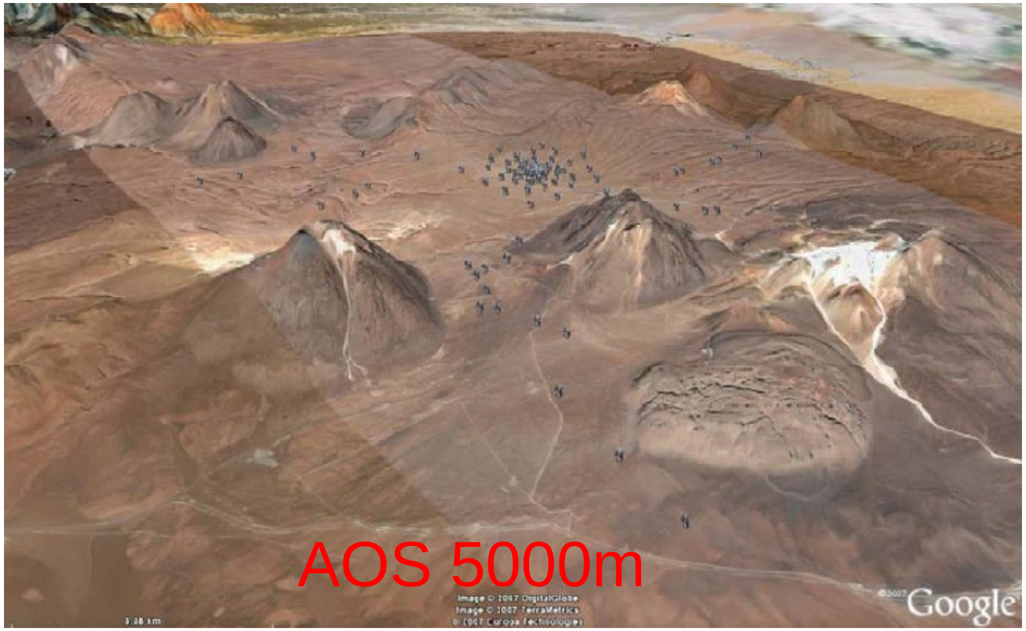
  5 mas for highest frequency/longest baseline
- Field of view / arcsec ≈ 17 (λ/mm) [12m dish]
- **Sensitive**, wide-band (currently 8 GHz) receivers; full polarization
- **Flexible** digital correlator giving wide range of spectral resolutions.
- **Software**

ALMA Receiver Bands

All atmospheric windows 35 – 1000 GHz



Sites


AOS 5000m
Google


• A "new village" in the desert
• Antenna construction & integration
• Technical labs, dormitories, etc.
• ~500 people during construction
• ~120 people during operations
OSF 2900m


Santiago Central Office

ALMA Collaboration

- International collaboration between Europe (ESO), North America (USA: NRAO; Canada: Herzberg), East Asia (Japan: NAOJ, Taiwan: ASIAA; more recently Korea).
- Hardware and software built across partner regions 1999 - 2014.
- System integration, verification, science commissioning in Chile.
- Approximate construction cost €1.2 billion; shared 37.5% each Europe and North Americal; 25% East Asia.
- Construction deliverables from each partner by agreed value.

ALMA Timeline

- c1983-90's Idea of a large mm/sub-mm array in USA, Europe and Japan.
- 1992-95 Site search and testing
- 1999 European/US MoU for design and development
- 2000 Prototype antennas ordered
- 2003 Europe-NA bilateral agreement
- 2003-5 Antenna tests at VLA site
- 2004-5 Rebaselining of bilateral project
- 2006 Trilateral Agreement Europe-NA-EA
- 2007 First antenna in Chile
- 2009 First antenna at 5000m
- 2011 Start of Early Science Cycle 0 (16 antennas)
- 2013 All 66 antennas integrated
- 2014 >1000 baselines
- 2014 Long baseline campaign
- 2015 Oct 1 Start of Early Science Cycle 4 (last before full operations)

Not an unusual duration for an international mega-project!

ESO Deliverables

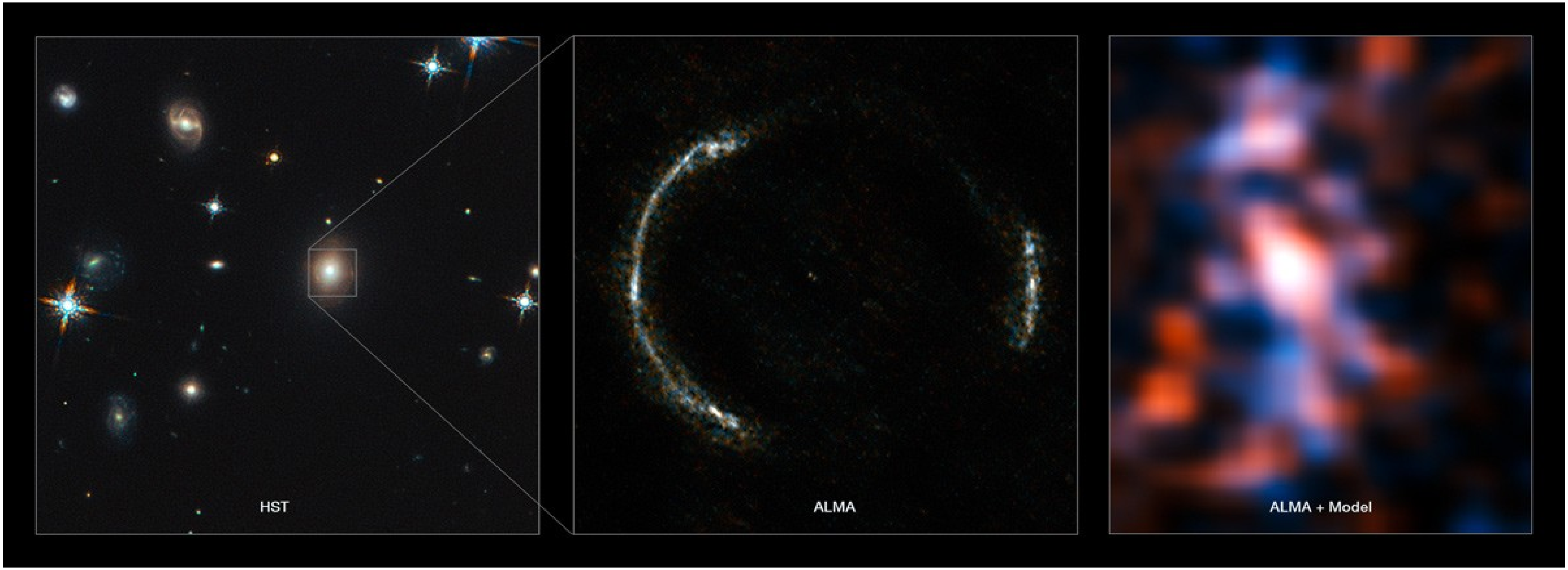
IPT / Subproject	Europe	North America	East Asia
Site Development	ALMA Road to OSF & AOS OSF Technical Facilities OSF Residencia Santiago Central Office ALMA Power Supply to AOS 192 Antenna Foundations	Roads at AOS AOS Technical Facilities AOS Utilities	Financial Contribution to costs (20%)
Antennas	25 Antennas (12m) Two Antenna Transporters	25 Antennas (12m)	4 Antennas (12m) 12 Antennas (7m)
Front End	Band 7 (73) Band 9 (73) Cryostats (70) Water Vapour Radiom. (53) Calibration Systems (70) 26 Integrated Receivers	Band 3 (73) Band 6 (73) Monitor and Control 26 Integrated Receivers	Band 4 (73) Band 8 (73) Band 10 (73) Integrated Receivers
Back End	Photomixers (hundreds) Digitizers Digitizer Clocks Multiplexers	Optical Transmitters Local Oscillators Digital Formatters Digital De Formatters	
Correlator	Tuneable Filter Boards	Correlator for 64 Ant	Correlator for 16 Ant
Computing	Software (lots)	Software (lots)	Software (lots)
SysEng & Int.	System verif., acceptances, documentation, enclosures, …	System verif., acceptances, documentation, …	System verif., acceptances, documentation, …
Science	CSV & science	CSV & science	CSV & science

ESO Team and Budget

- Snapshot 2011 (maximum): 32 FTE ALMA Division + 16 FTE from matrix and general services + 9 FTE external
- ESO primarily contracted to:
  - European industry
  - European institutes (IRAM, U Bordeaux, RAL, NOVA, ...)
- Some construction work done in-house, but not much
  - Major difference in approach from NRAO and NAOJ
- Total ESO construction spend 505-35 = 470 M€
- Includes Residencia (currently under construction)
- ~1.5% over budget set in 2005
  - Mostly building costs
- All (9%) contingency spent

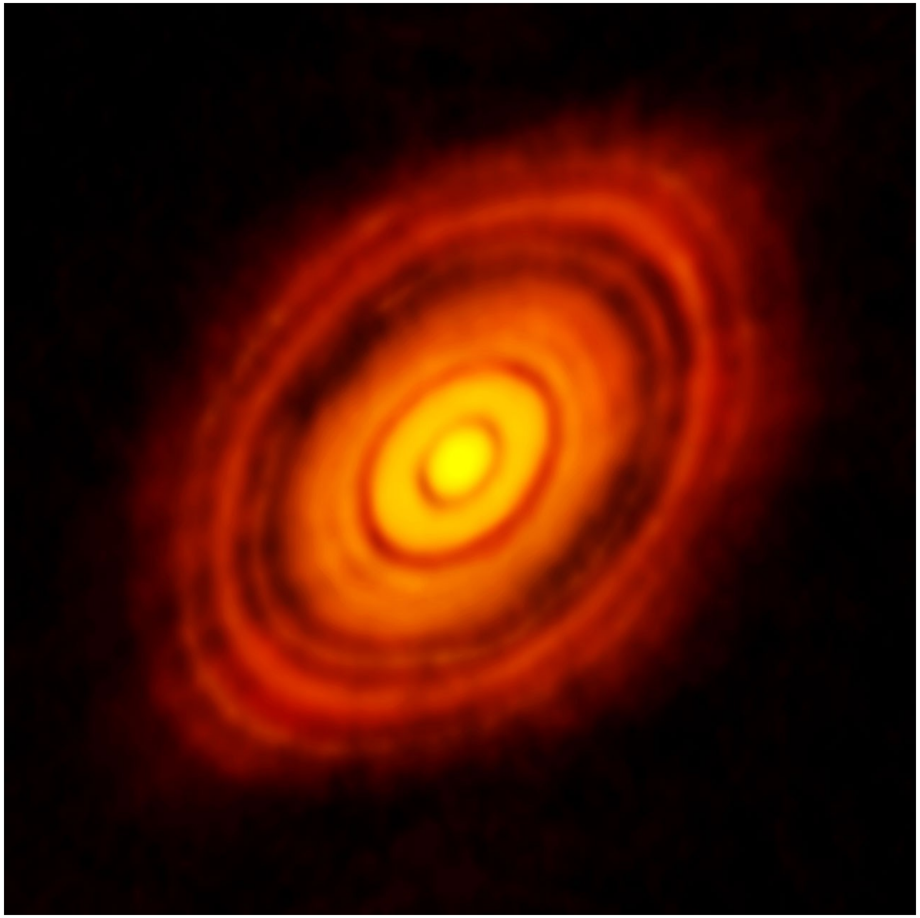
ALMA works!

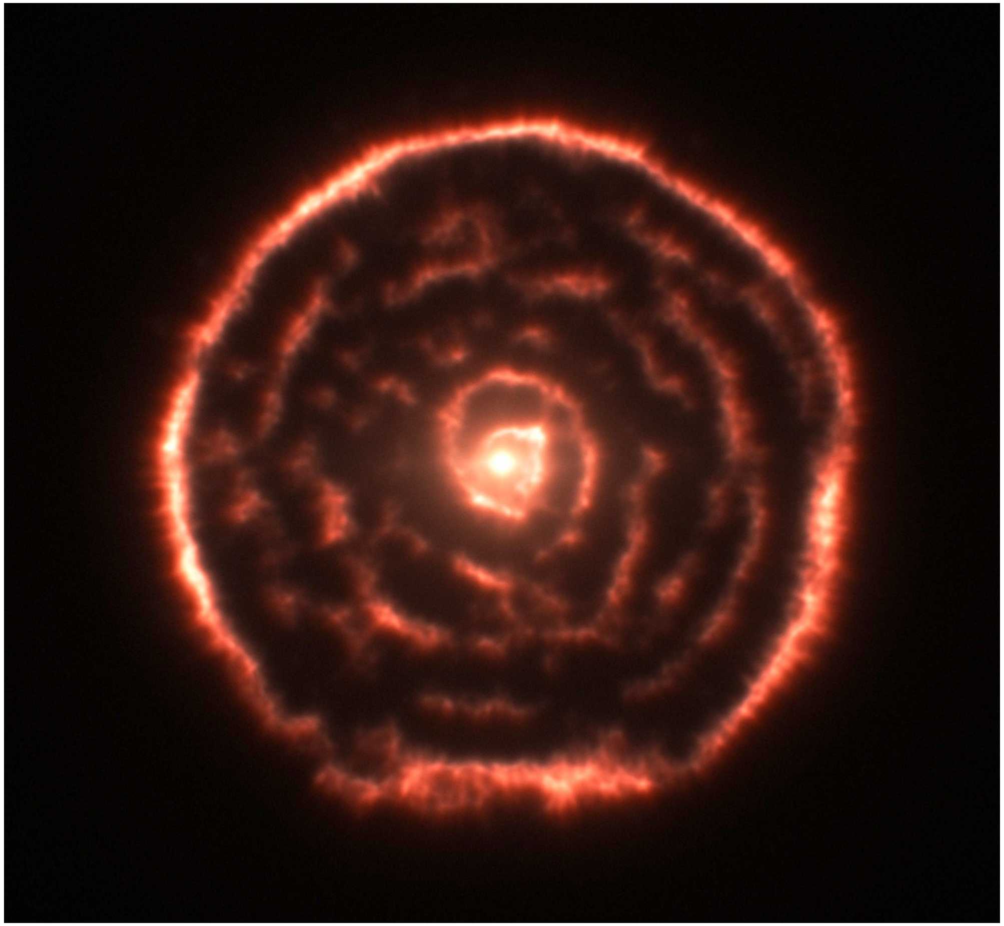
- 275 refereed publications as of September 21
- ~6% Nature/Science
- Wide range of science
- Huge oversubscription



Gravitational lens SDP81

More ALMA Science





HL Tau protoplanetary disk
Dust continuum 230 GHz

R Sculptoris carbon star
CO3-2 line 345 GHz

Key Advances

- Collecting area
- Antenna surface accuracy, pointing
- Spatial frequency coverage (number of antennas)
- Receiver noise temperature and bandwidth
- Atmospheric transparency and phase stability
- Frequency range
- Baseline length

Aim to outperform existing arrays (CARMA, SMA, Plateau de Bure) by several of these criteria simultaneously, and by factors ~10.

Challenges

- New technology
  - e.g. high-precision CFRP antennas
- Phase stability
  - Long baselines
  - LO distribution
  - Troposphere: water vapour radiometry, fast switching
- Demanding receiver noise specifications
- Custom-made equipment
  - antenna transporters
  - digitizers
- Transition from one-off to series production
- High site in remote location
- Complex international partnership

Technical Status

- Basically built within specification and 2005(!) budget
- Technical choices ~95% correct
- Main outstanding issues
  - Reliability in operation
    - Many minor problems, rather than a few major ones
  - Vertex antenna surface setting
  - Non-linearity issues for total power
  - Full commissioning of all modes, e.g.
    - solar
    - subarrays
    - wide-field polarization

Lessons Learned

Rebaselining

- Original budget (set in 2000-1) was over-optimistic.
- Even early on in the project, significant descopes were made
  - 4 receiver bands
  - no VLBI

But capabilities not designed out.

- Cost to completion appears to be solidly known only once the design process is well advanced and the **real** costs of major external procurements are known.
- For ALMA, this was in 2004-5, six years after the start of serious work on the project
- Rebaselining in 2004-5 was centrally coordinated, fast.
  - Main change was 64 → 50 antennas
  - Also agreed increase in bilateral budget
- For ESO, the final cost to completion is within 1.5% of the budget set in 2005

What was underestimated?

	Y2002/Y2000$	Ratio
1 Management / Admin.	18	4.6
2 Site Development	71	1.9
3 Antenna Subsystem	230	1.3
NA Antenna Procurement		
EU Antenna Procurement		
4 Front End Subsystem	112	1.0
5 Backend Subsystem	50	1.1
6 Correlator	15	0.7
7 Computing Subsystem	36	1.1
8 System Eng. & Integration	21	2.2
9 Science / EPO	10	1.0
Total	562	1.4 avg

Bilateral Project

Analysis in 2005

Rebaseline project: 40% increase

Site: construction in Chile and power
Antenna: steel, CFRP
SE and management: unrealistic for a big international project

Restoring lost scope

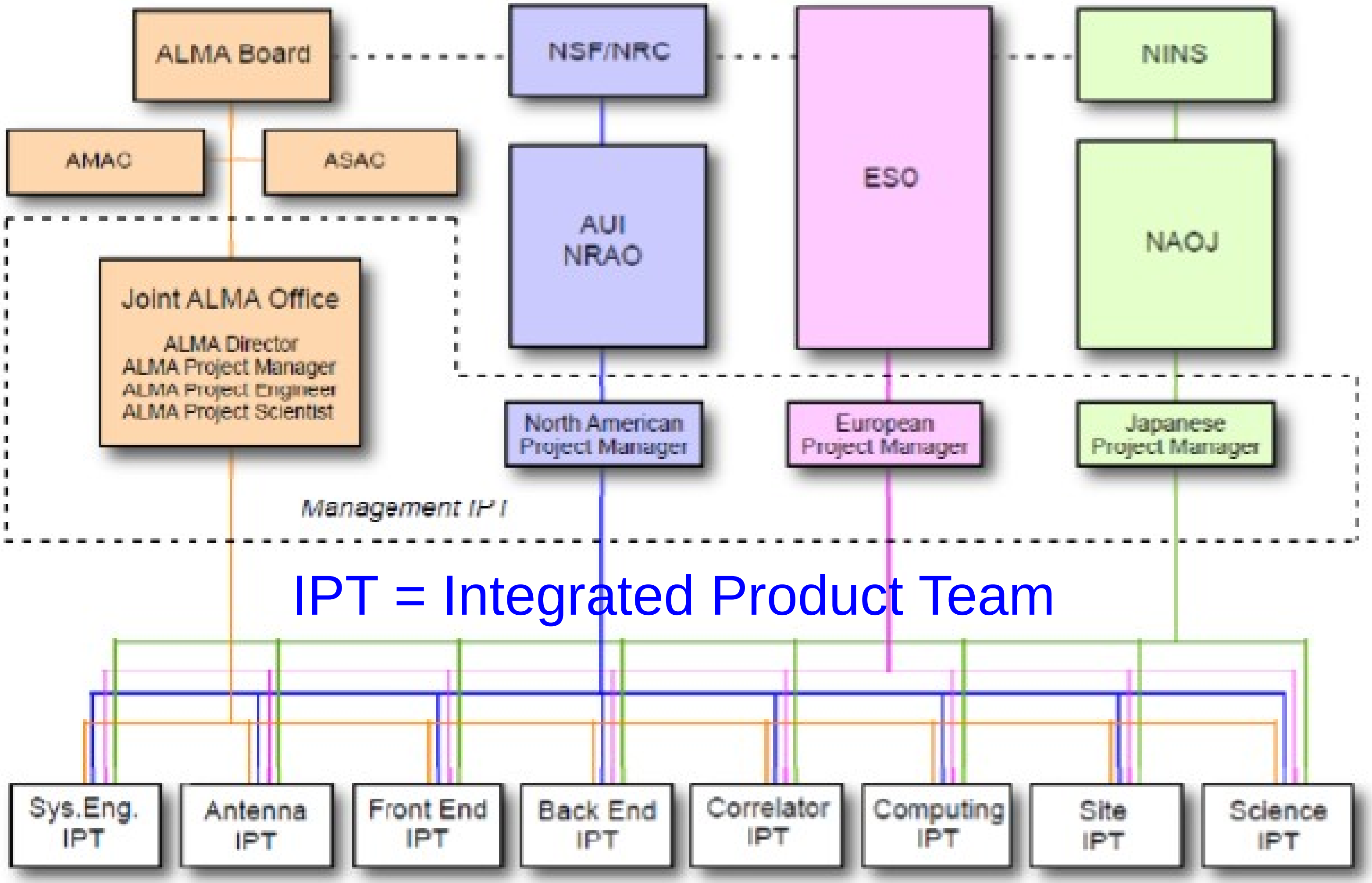
- New partner
  - East Asia: three receiver bands (and the ACA) – now operational
- Development Programme
  - Phased array and VLBI - test (Cycle 4)
  - Solar observing – test (Cycle 4)
  - Band 5 (167 - 211GHz) - deployment in progress
  - Band 1 (35 – 50 GHz) – CDR Jan 2016
  - Band 2 (67 – 90 GHz) – prototypes under test
  - Design studies for upgrades (sideband separation for Band 9; improved digitizers; correlator; wider IF bandwidth; data rate; software; ...)

If you descope, provide and demonstrate to the community that there is a path to full capability and beyond.

Lessons: budget

- Your initial budget is likely to be over-optimistic. Allocate a large contingency.
- Costs appear to be known to ~10% when the main contracts for the main deliverables have been placed.
- If you need to rebaseline at that point, do so centrally and quickly.
- Beware of infrastructure costs, which are particularly vulnerable to political and economic factors outside your control.
- Don't design out capability. Provide a way to get it back later, or if new partners join.

Management Structure (Construction)



Obvious tension between regional executives and JAO. Complexity.

(Dis)Integrated Product Teams

- Some teams completely integrated: science; computing
- Most became very well integrated (front end; back end; correlator; system engineering)
- Site and antenna teams poorly integrated
  - Antenna testing would have been better done by a single team; pool resources to avoid errors
  - Serious issues with interfaces between power generation and distribution systems made worse by lack of communication between regions
- Recommend training at the start of an international project
  - Working culture and practices
  - Organizational constraints (funding cycles, reporting, procurement practices, ...)
  - We got used to these, but it took some time

Governance

- Governance model
  - ALMA is a partnership, not a legal entity
  - The ALMA Board oversees the whole project
    - Separate representation of NSF, AUI, NRAO and Canada on NA side + matching EU, EA – really too large
    - Executive Directors are Board Members
    - Directors' Council has improved things
  - JAO manages construction and operations in Chile
  - ALMA Director leads JAO
  - Executives retain responsibility for construction in the partner regions

This model was made to work, but with considerable effort.

Consequences

- Highly variable relations between executive and JAO project managers
  - (Usually) much better at working level
- Clearer definition of role of JAO was needed
  - Take responsibility (and budget) for system-wide activities: system engineering, integration, acceptance and commissioning; local site infrastructure.
  - Work in close collaboration with the regional executives.
- Some activities worked well
  - AIV of antenna elements
  - Rebaselining
- Others went badly
  - Commissioning of power generation and distribution system

Staffing

- Maintain continuity, in project manager positions
  - Not ideal at ESO initially or at JAO throughout construction
- Recruitment and retention of key personnel at remote sites is hard
  - JAO recruitment started far too late and turnover has been high
  - ESO VLT approach of staff moving from construction in Europe to integration and commissioning in Chile (mostly) did not work
    - inconsistent with series production
  - Think hard about motivating people
- Continuity within IPT's and institutes was (unsurprisingly) much better

Science

- Broad community consensus on science
  - Converged rather quickly
  - Design reference science programme
  - Process was a lot less elaborate than equivalent for SKA
- Science IPT very well integrated
  - No real regional differences in scientific priorities
  - Reasonable balance between outward facing (community) and inward facing (working with engineering teams)
- Advisory Committees
  - ALMA Science Advisory Committee (ASAC) + 3 regional SAC's
  - Functioned well during construction (members selected to have technical expertise)
  - Essential role in advising on what to do first: kept the community content with the process

Science team roles

- Inward facing
  - Work with engineers
  - Translate science ↔ engineering requirements
  - Trade-offs
  - Tests, simulations, calibration, ...
- Outward facing
  - Work with science community
  - Understand science opportunities and requirements
  - Advisory committees

These roles are both vital: encourage dialogue between astronomers and engineers but write down the requirements.

Science Requirements

- ALMA top level science requirements were enough to set the broad scope of the project – no more
- Lower-level science requirements were insufficiently precise
  - also sometimes muddled with engineering requirements
  - mitigated by a very comprehensive set of system level technical requirements (see later)
  - caused occasional problems in assessing cost/performance trade-offs
  - some tolerances too tight → cost increase or delay
- Not updated when the scope of the project changed (e.g. rebaselining)

Commissioning

- Levels of effort and (particularly) skill underestimated
  - Planning affected by late delivery of hardware and software
  - Decision to run commissioning and early science in parallel was essential, but meant that operations staff had much less time available for commissioning.
  - There were very few experienced people
    - In demand for other projects
    - Not always interested in long-term move to Chile
    - Those that did move were extraordinarily effective
- Better planning needed for:
  - Medium-term (3 – 6 month) visitors
  - Motivated and hard-working, but inexperienced people
  - Transition from commissioning to operations (unified team)
  - Commissioning team science and motivation

Systems Engineering

- Main tasks of SE IPT:
  - Technical and process
  - Product Assurance
  - System Integration; Assembly, Integration and Verification
  - System Verification
  - ALMA Test Facility at VLA site
- Scope initially **badly underestimated**
  - Good system architecture
  - Informal approach
  - Little effort on systems engineering process
  - Documentation, change control transferred too early to JAO
  - JAO later developed a stronger SE group, but this was not continued for long enough

System Architecture and Requirements

- System architecture proved to be well-designed and robust
  - Tribute to the original designers
  - Robust to rebaselining and additions (e.g. ACA)
  - Close to a waterfall model: not clear what would have happened if major changes had been necessary
  - ESO should have had more expertise in-house
- System level technical requirements were very well specified
  - Deliberate attempt to set very challenging specifications
    - Serious doubts in some quarters initially (LO distribution, noise, ...)
    - Noise temperatures in frequency range 150 – 700 GHz better than specification (advances in SIS junction technology)
  - Most other specifications met, but not with much margin
    - A few issues with flow-down to sub-systems (tolerance too tight)
  - Process was effective but quite informal
    - Performance budgets were produced, but very late

Interfaces

- Sub-system interfaces
  - Mostly well-defined: few instances of sub-systems failing to work together (except site infrastructure)
- Interface Control Documents (ICDs)
  - Absolutely essential to the success of ALMA as a distributed project
  - Rigorous and exhaustively documented in most areas (again, except site infrastructure)

Reviews

- Standard procedure evolved from existing ESO model
  - Conceptual, Preliminary and Critical Design; Manufacturing Readiness; Test Readiness
- Compromises essential
  - Some (at least initially) saw reviews as unnecessary bureaucracy
  - Others tended to focus on trivia
  - ESO initially (perceived as) inflexible, paying too much attention to form and too little to technical issues
- Process came to work well in most areas
  - Effective working groups – kept continuity
  - Particularly good for receivers (cooperation across regions)
  - Serious problems with antenna and site (little cooperation)

Reviews: some lessons

- All parties need to respect each other
  - ESO had to develop expertise in-house or to find support from its community
  - Avoid “them and us” and “they aren't listening to us, so we will not participate again”
- Everyone needs to understand the value and purpose of reviews
  - Tool in managing a distributed project, not an end in themselves
  - Key stakeholders must be involved and active (science as well as engineering)
  - Follow-up is crucial
- Make the process as painless as possible
  - Tools for capturing questions and discrepancies

Antenna

- Prototypes
  - Original idea was to evaluate two prototypes, select the better one and issue a call for "build to print"
  - Failed because prototypes were late and neither actually met the full specification (some differences of opinion ...)
  - Therefore issued calls for "build to specification"
- EU Antenna Contract (the bare facts of a messy process)
  - Cheapest compliant bidder to ESO at contract opening was Vertex Antennentechnik
  - Contract was not signed in 2004 ◄ Serious risk of project cancellation!
    - clarify performance
    - request from ESO FC to Council to confirm that rebaselined ALMA was affordable
  - Vertex and AEM made opposite price changes in Sept 2005, making AEM the cheapest bidder
  - Contract signed in Dec 2005

Antenna Production

- 18-month redesign process was barely enough
  - major changes from prototype to production
  - lots of analysis by ESO
  - pre-production model?
- Difficulties of integration on site in Chile seriously underestimated by AEM Consortium
  - Local conditions
  - Communication
  - More pre-assembly in Europe?
- Acceptance and test
  - Major effort from ESO to support contractors
  - Prototype test equipment (OPT, holography system)
  - Lack of integration between regional antenna teams led to duplication of test procedures (but this was probably a good thing in the end ...)

After all that ....

25 very good antennas delivered in 29 months.

Procurement lessons from the antenna contract

- Everyone, **including governing bodies**, must respect the rules
  - ESO has very stringent regulations, for good reasons
  - Legal monitoring
- Bids must remain valid for an adequate time to allow contract negotiation
- Do not allow governing bodies to become involved in evaluations of industrial bids
- Conversely, demonstrate to them unequivocally that evaluations are fair and rigorous
- Fair geographical return must happen, but should be separated (as far as possible) from contract evaluation.

Front End (1)

- Institute contracts
  - Band 7 (IRAM), Band 9 (NOVA), Cryostat (RAL), ..
  - Not our usual model, in which ESO funds hardware and consortia provide FTE's in return for guaranteed time.
  - Instead, fixed-price contracts with outside purchases reimbursed directly; no GTO.
  - Initially some doubts, but worked well in practice, e.g. both Band 7 and 9 were delivered on time, within budget and well within noise specification
- Industry contract for water vapour radiometers
  - Again some doubts, this time that an industrial company could do a good job without institute collaboration
  - Also worked well

Front End (2)

- Front End Integration Centre (RAL)
  - Started too slowly
    - Late delivery of test equipment
    - Slow ramp-up of resources/staff retention
  - In the end, delivery rate matched that from other FEICs
  - Decision to move some production to EA FEIC
    - May not have been necessary in hindsight

Back End and Correlator

- Digitizer assembly and Tunable Filter Bank Cards
  - Both started as custom development (U Bordeaux)
  - Working with industrial partners
  - Good procurement model

Computing (1)

- Requirements
  - On-line software fairly well thought through (SSR)
    - Observing overheads not properly included
  - Operations software not properly specified
    - e.g. project tracker, shift log tool, archive query
  - Simple low-level system to test the hardware
    - never specified
- Started too late
  - Operations software
- Started too early
  - Pipeline (heuristics not there; foundations changed)
    - CASA-based calibration pipeline now working
    - Imaging pipeline almost there

Computing (2)

- Initial impressions of on-line software were **very** negative: why?
  - Slow, crashed a lot
  - Monolithic releases
  - Designed as an integrated system with little low-level functionality accessible to users
    - any error required a “full system restart”
- Recommendations
  - Modular releases
  - Testing
  - Simulation
  - Make computing part of the commissioning team

Site Infrastructure

- Most problematic area in ALMA construction
  - Complexity of engineering issues underestimated
    - Weak system design
    - Too few qualified engineers to supervise
  - Split between partners not well-defined
    - Power generation and distribution systems
    - Antenna stations
  - Site IPT not communicating internally
- Environmental specification
  - Snow-line can be ~500m higher than expected in Chilean building code
    - Road damaged by rain
  - Risk assessment not adequate
    - Informed decision on whether to build extra culverts

Site Infrastructure Recommendations

- Do not split procurements artificially for political or cost-balancing reasons (especially between members of a partnership)
  - “artificially” means in a way that does not make engineering sense or generates unmanageable interfaces
  - If you have to split, you need clear interfaces and a robust overall system design
- Never underestimate the difficulties of civil engineering – buildings, roads, power.
- Rigorous environmental assessment, including the effects of rare events (weather, earthquake, ...).
- Supervision should be done on-site, not remotely.
- Well-qualified, experienced staff to supervise site contracts.
- Effective use of local contracts and procurement and legal services.

Procurement: general

- ESO procurement procedures worked reasonably well for ALMA (site and antenna were exceptions)
  - Contracts and Procurement should have been integrated into the team rather than keeping them as a separate service
  - Some cases of underbidding – dealt with by normal processes
  - Some deliveries were late and penalty clauses were applied
- Contracts with institutes were in general very successful
  - e.g. receiver bands, digitizers, tunable filter bank cards, ...
  - Firm fixed-price contract: no guaranteed time (cf. VLT)
    - Risk caused some institutes to put in very high bids
  - Third-party purchases reimbursed at real cost
  - Penalties not appropriate
  - Problems solved by pressure at management level

ALMA at ESO

- ALMA construction was never really integrated within ESO
  - “ALMA is not an ESO project”: not seen as part of ESO's core mission
  - Small core team – tended to be isolated within ESO, although highly engaged with the project.
  - Reluctance to recruit and retain staff with specialized skills in sub-mm science and technology
  - Internal exile to a distant part of the campus did not help.
- But some existing departments contributed a lot
  - Contracts and Procurement
  - Mechanical Analysis
  - EMC
  - Control Engineering
  - Software

Strategy for new projects at ESO

- If in-house expertise is limited, ESO should plan to hire or train a small number of specialists.
- People working at the science/systems/software boundaries are particularly valuable, as they tend to have a good overview of the entire project.
- Experts in key technologies are also important.
- The intention is not to replace outside expertise, but rather to provide a nucleus of people who can interact effectively with the community.
- Involving member state institutes is vital, either through full funding (as for ALMA) or part funding and guaranteed time (as in the VLT model). The former mechanism is more appropriate for series productions and for groups more interested in the technology than in science exploitation.

Any lessons for SKA?

- Yes
  - Core team must have the numbers, experience and expertise to work with and retain the respect of the community and industrial partners.
    - The ESO sub-mm team was really too small ....
    - ... but could draw on engineering skills in closely related fields
  - Contract management is crucial
    - ESO had (a very few) experienced and able project managers who had worked on VLT and transferred to ALMA
    - Some key recruitments were made
    - Established Contracts and Procurement, Financial systems
- No
  - The problems of embedding ALMA in ESO, NRAO and NAOJ are probably not very relevant.

Common Themes from ESO, Institutes and Industry

- Comprehensive, clear and rigorous technical specifications and statements of work are essential
- Think hard about interfaces between sub-systems and document them.
- Treat Institutes as part of the project, not as contractors, but make sure that they deliver what is agreed (or better!).
- Community involvement is a huge asset, but make sure that you have enough expertise in-house to exploit it.
- Do not underestimate cultural or organizational differences.