Coordinated solar observations with ALMA:

Issues, constraints, how to plan them – an ALMA-centric view

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in collaboration with
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EUROPEAN ARC
ALMA Regional Centre || Czech

Astronomical Institute
of the Czech Academy of Sciences

Outline

- ALMA – a brief intro
  - EU ARC as your support infrastructure
- Solar ALMA observations: Current status, outlooks
  - Solar ALMA Observing Mode: Capabilities & limits
- Life-cycle of the solar ALMA observation project: From the initial idea to receiving calibrated images
  - Time constrains for solar ALMA observations
    - By season
    - By hour-of-the-day
  - Scheduling your project for ALMA observation
  - Communication line to JAO & ARC
- Coordinated observations with (selected) space-born observatories
- Including ground-based solar telescopes – a successful example
- Summary

What is ALMA?

- ALMA = Atacama Large Millimeter/sub-millimeter Array. The largest project of contemporary ground-based observational facility in astronomy built in a world-wide international cooperation in Chile
- The key partners are ESO, NRAO and NAOJ
- System of fifty 12m high-precision antennas + twelve 7m (ACA) phased as an interferometer, + four 12m single-dish (TP)

What is ALMA?

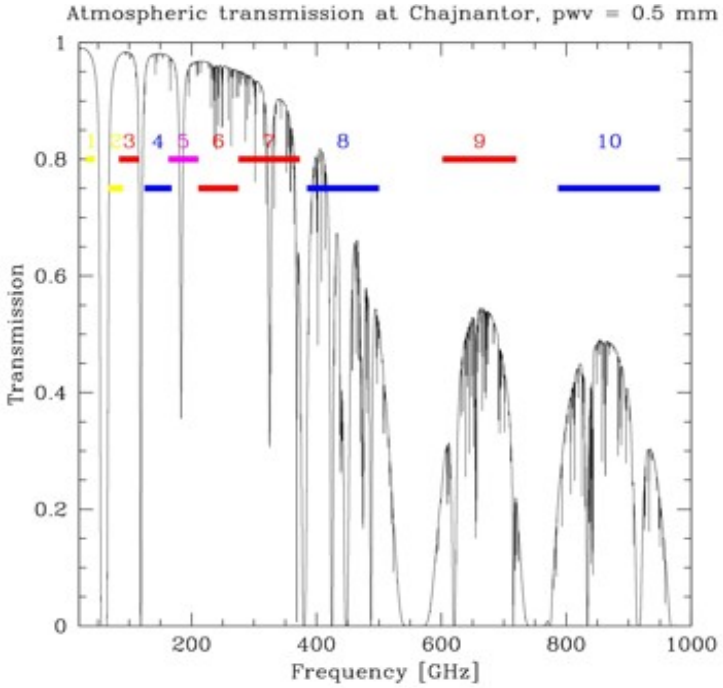

to Central America/ Caribbean
Venezuela
Guyana
Suriname
French Guiana
Colombia
Ecuador
Peru
Brazil
Bolivia
Paraguay
Argentina
Chile
Uruguay
Falkland Is.
South Georgia & S Sandwich Is.
©1996 Brandon Plewe
South latitude
22°
23°
24°
25°
West longitude
70°
69°
68°
67°
Ollague
Bolivia
Pacific Ocean
Calama Airport
Pampa la Bola Chajnantor region (5000m)
San Pedro de Atacama (2450m)
Chile
Port Antofagasta Airport
Paranal (2400 m)
Argentina
Taltal
100km

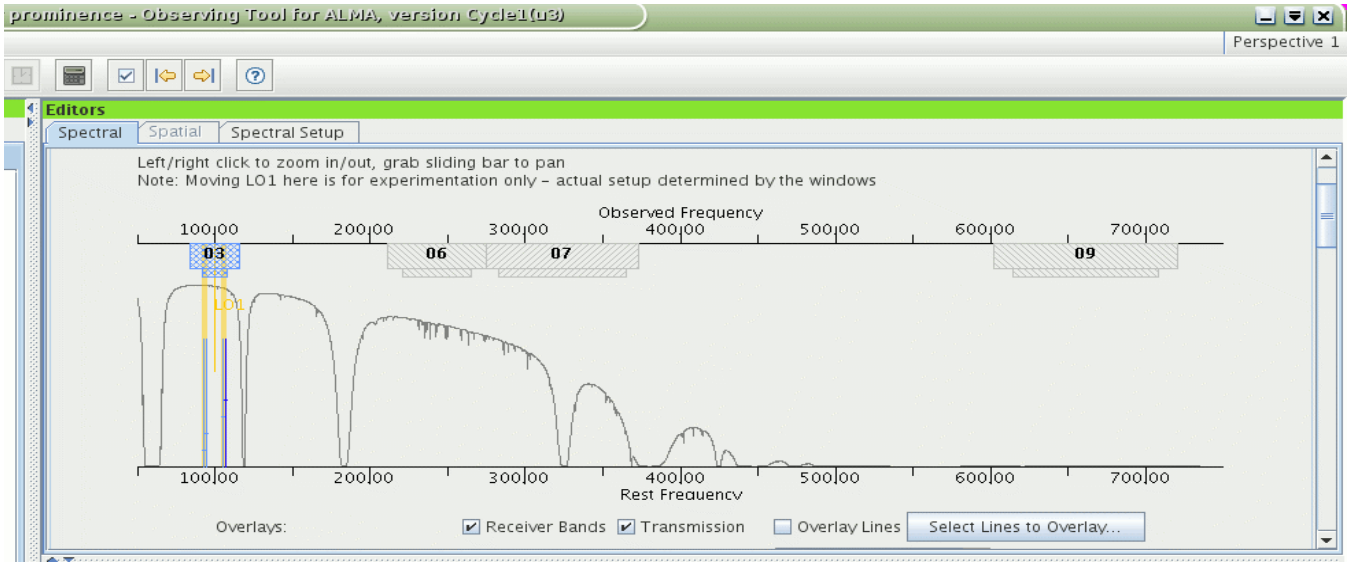
What is ALMA?

For the first time we (will) have

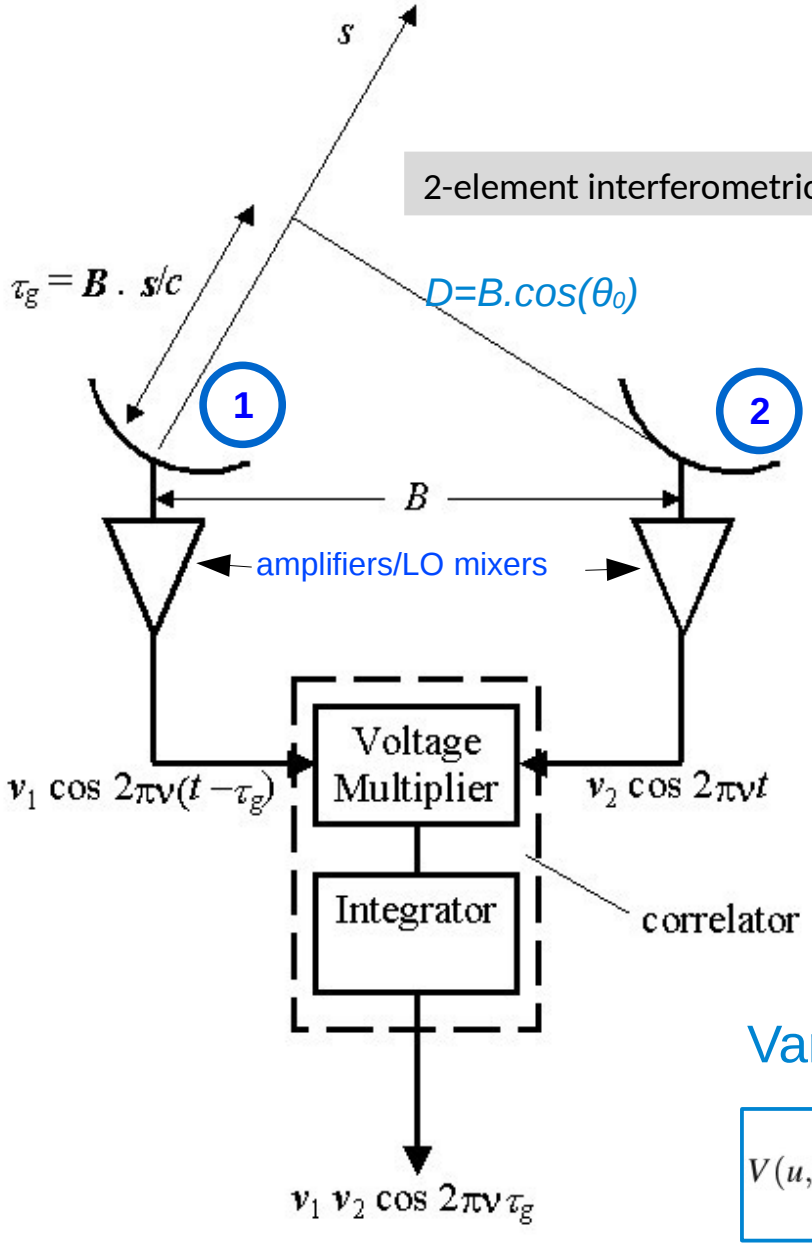
- Very high spatial resolution (up to 0.005“ in extended configuration @ 1THz ↔ 2m object at the Moon)
- Extremely high spectral resolution – up to 30kHz
- Temporal resolution for very bright sources (e.g. the Sun) > 1s
- Very high sensitivity

at the same moment in a broad range of frequencies from 30GHz up to more than 1THz

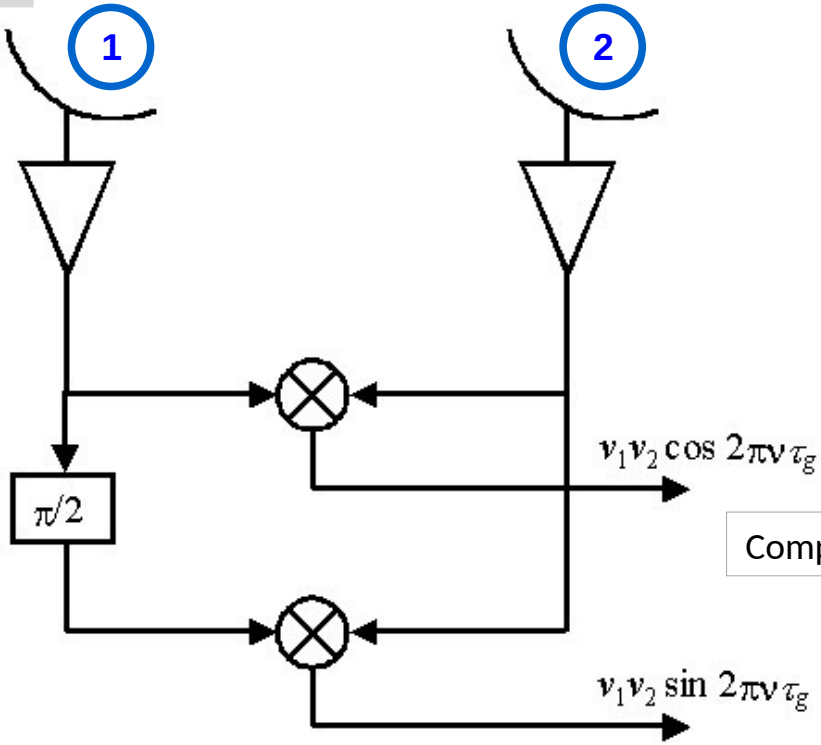




How does ALMA work?



2-element interferometric correlator



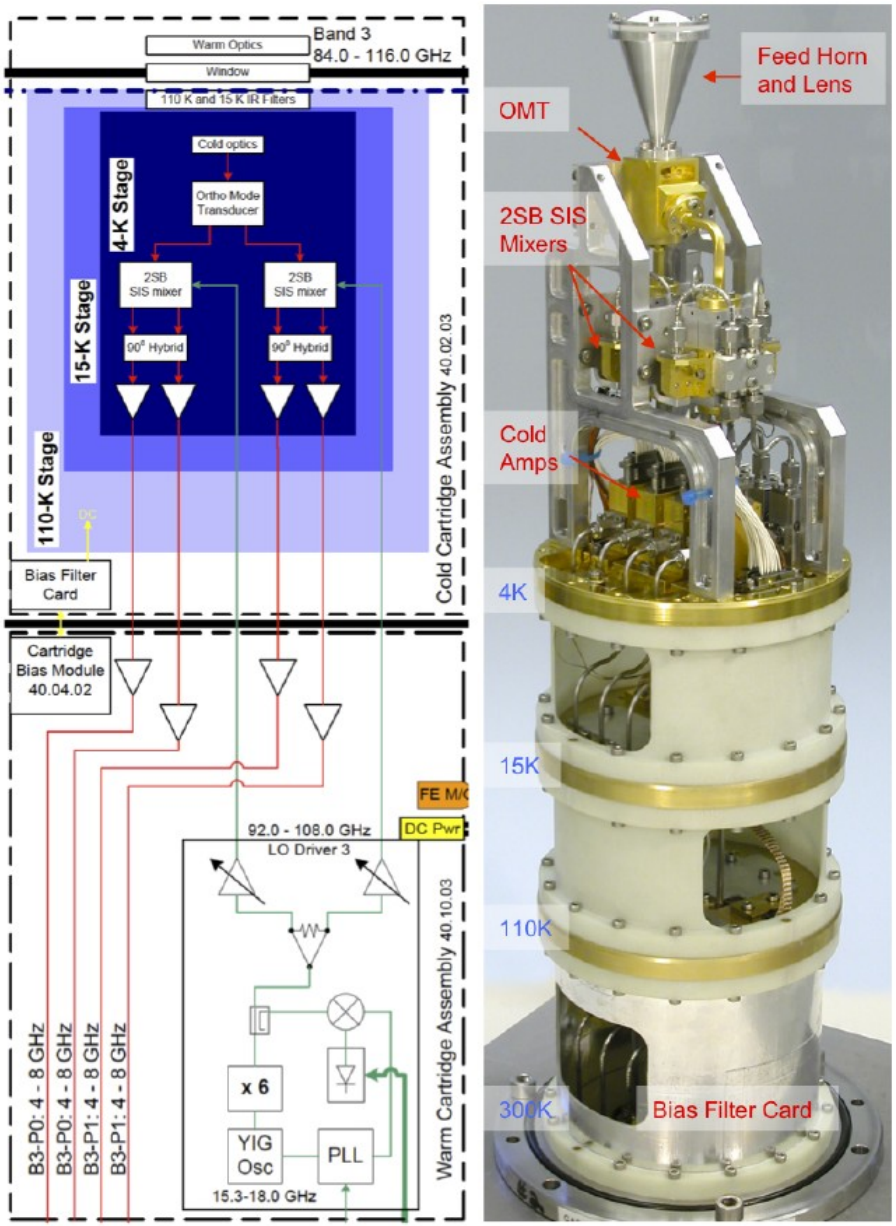
Complex visibilities

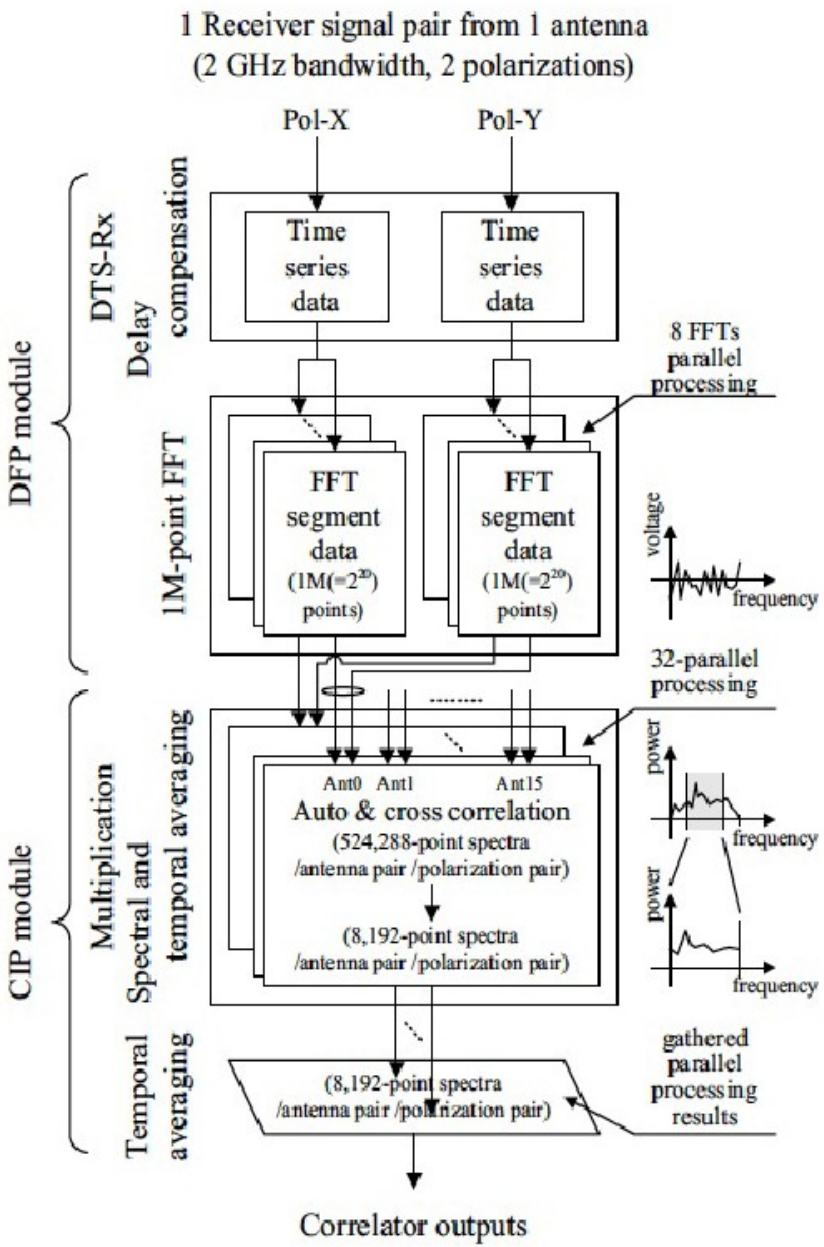
Van Cittert -Zernike theorem

$$V(u,v,w)\,e^{-i2\pi w} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(x,y)\,I(x,y)\,e^{i2\pi(ux+vy)}\,dx\,dy$$

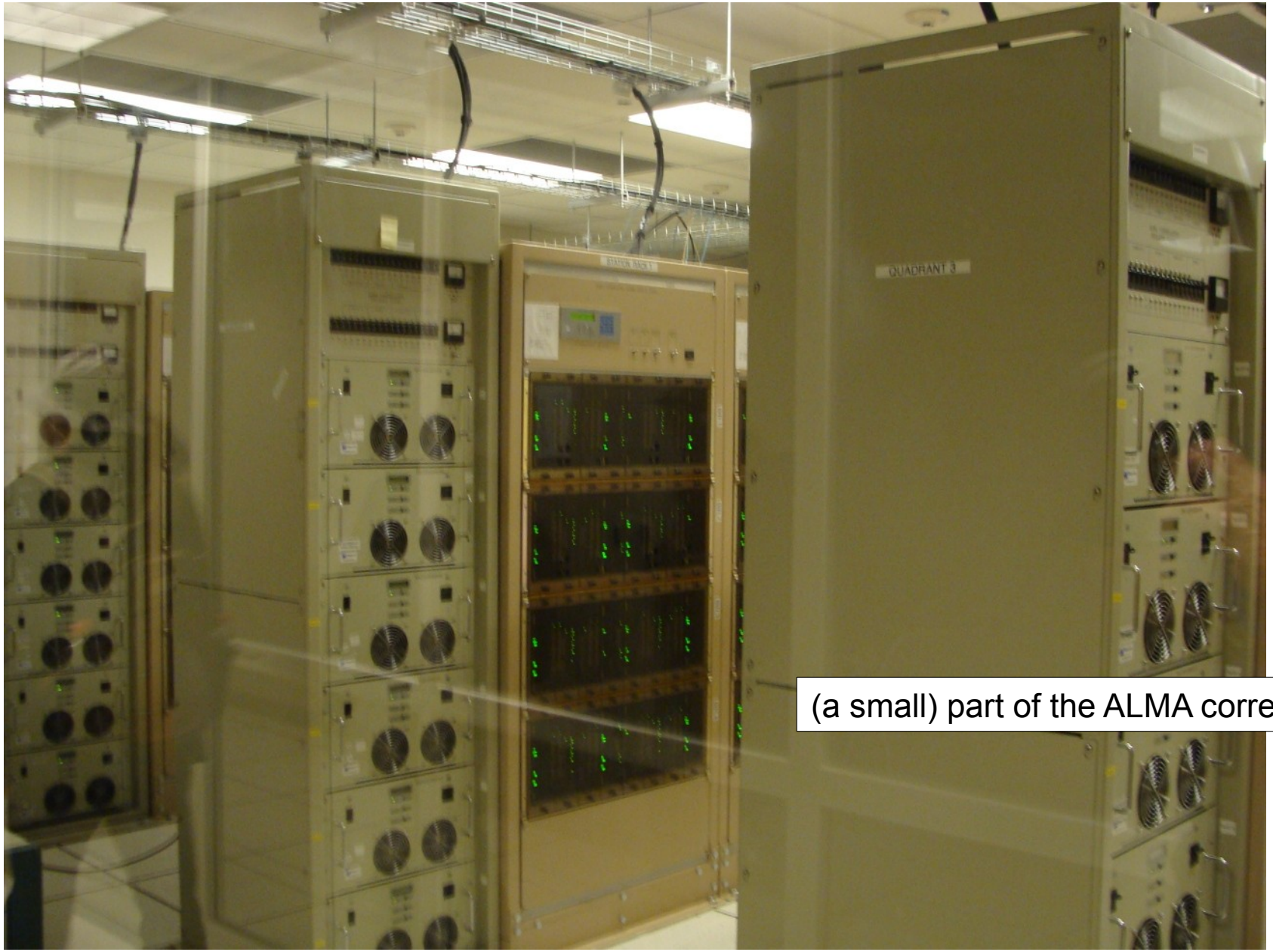
$$\langle P_{12}\rangle = \langle U_1 \cdot \overline{U_2}\rangle$$

ALMA hardware



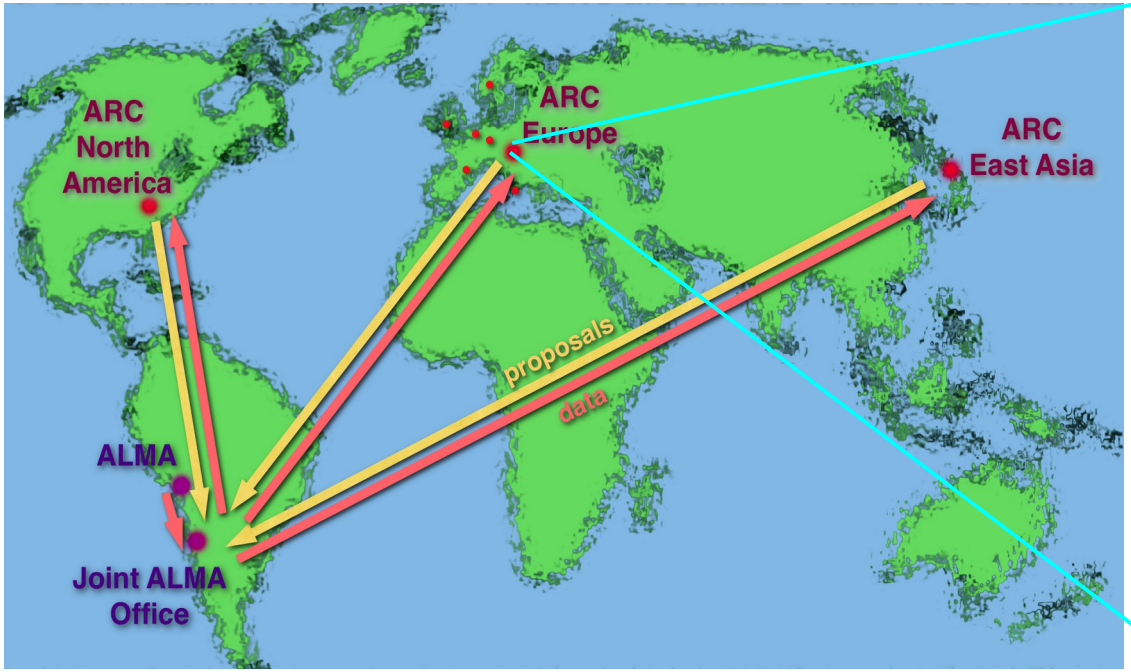


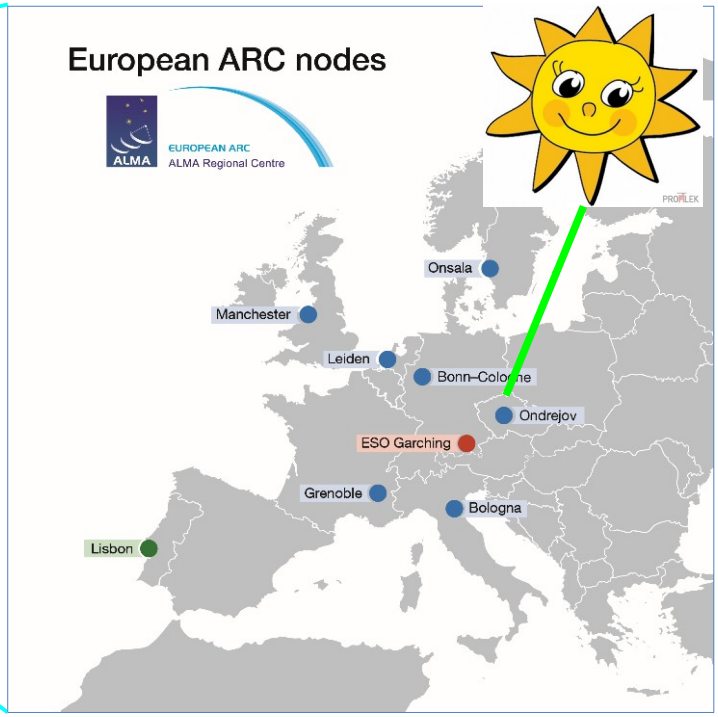
ALMA hardware



(a small) part of the ALMA correlator @AOS

ALMA Regional Centers / ARCs and the ARC nodes





ALMA Regional Centers – ARCs:

Supporting infrastructure – interface between ALMA observatory and user community
User support & **help with ALMA development**

Structure of the European ARC:

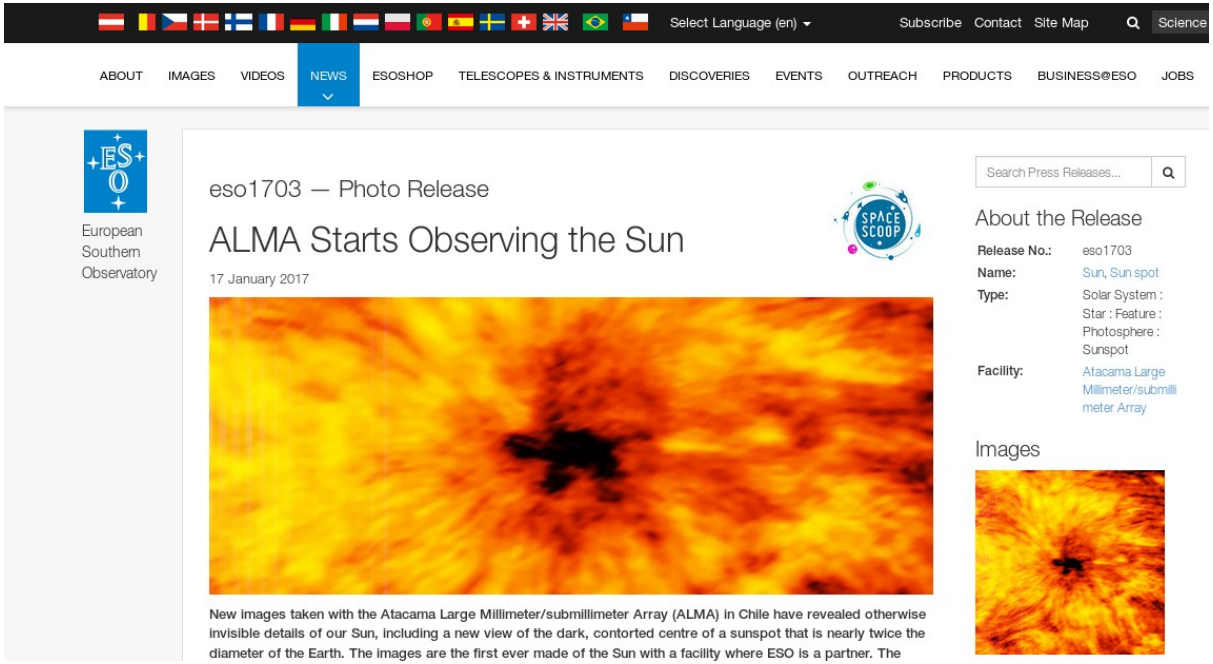
- Head in ESO Garching
- Seven nodes across Europe
  - **<u>One in Ondřejov (Prague), Czech republic
Unique (in Europe) expertise for solar ALMA observations.</u>**

EUROPEAN ARC
ALMA Regional Centre

Acceptace of the *Solar ObsMode* – Start of solar science with ALMA: Since Cy4 (Spring 2017)

Solar ObsMode

- Accepted as a non-standard science mode for Cy 4 with limitations
- Summary of CSV published in two Solar Physics papers
  Fast-scanning TP: http://adsabs.harvard.edu/abs/2017SoPh..292...88W
  Interferometric obs.: http://adsabs.harvard.edu/abs/2017SoPh..292...87S
- ESO press-release no 1703 (also ALMA Science Portal news)



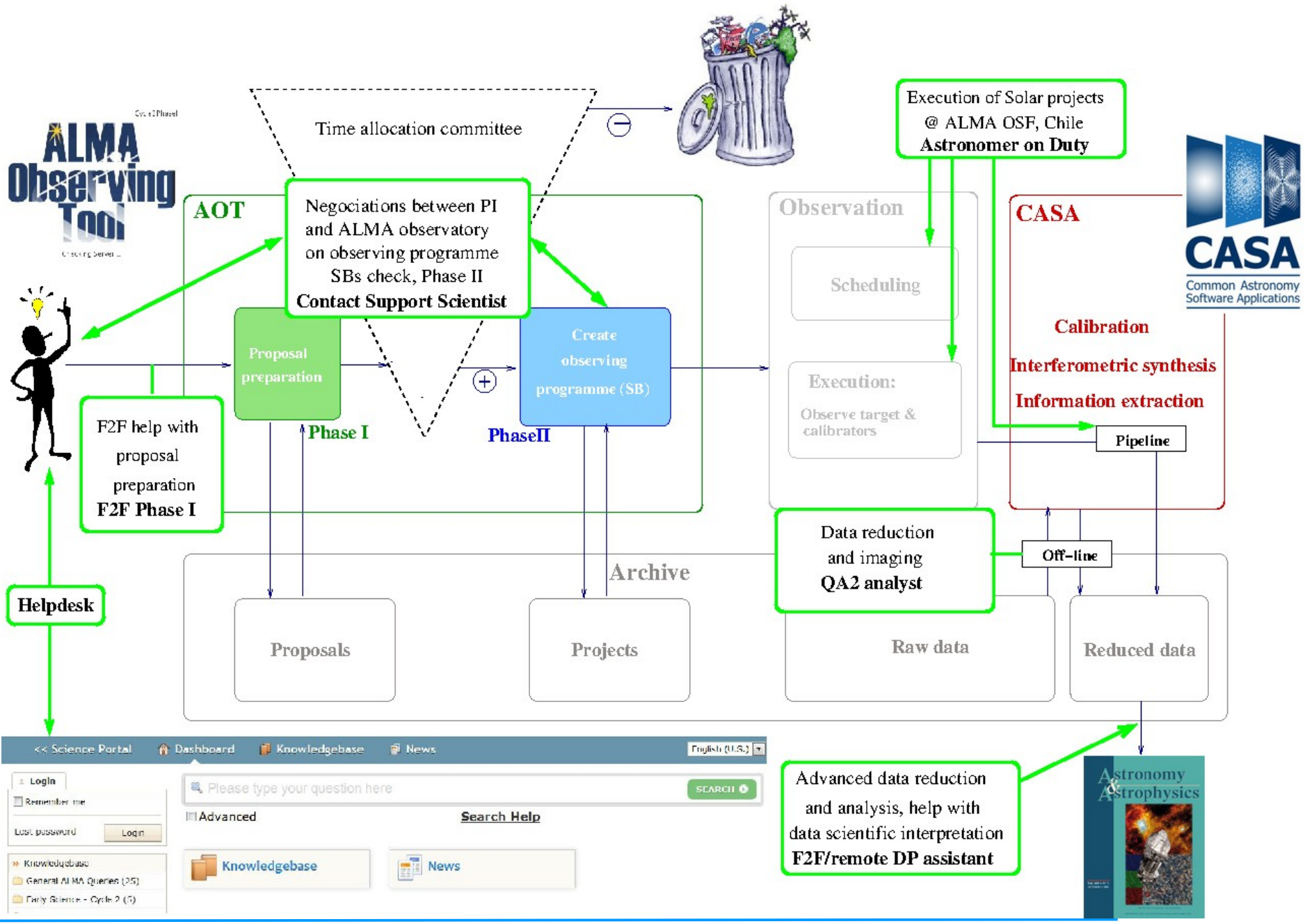
Solar ObsMode: Current specifics & limitations

- **Non-standard mode**
  - Limited capabilities: Bands 3 & 6 (Band 5 since Cy8) only, TDM only (i.e. 128 channels per 2GHz SPW), **configurations limited to ≤ C43-3** (43-4 for Band 3), no polarization,...
  - Combined 12m+7m array, always have complementary TP maps (entire Sun – fast-scanning mode; no regional TP map so far).
  - Using SIS mixer detuning (MD) approach for attenuation of too strong signal from the Sun. Likely not sufficient for flares.
  - **Ephemeris targets** (solar motion among stars + solar diff. rotation).
  - Literally manual calibration & imaging (even no *Script Generator* so far).
- **Solar science goals are mostly *Targets of Opportunity*** by matter (but not technically).
- The Sun is dynamic/highly variable – Need advanced data post-processing (time-domain imaging + self-calibration) beyond the standard data calibration and synthesis done at ARCs in frame of the QA2 data processing.

Solar ObsMode: Outlooks

- Bands 5 & 7, polarization (already being tested – EA ARC, JAO)
- Automated data processing (standard QA2) – Solar Script Generator (under development, Ondrejov), later ALMA pipeline integration
- Advanced data post-processing (time-domain imaging +self-cal: under development – UiO, NA & EA ARCs)
- Extended baselines (C43-4+) - an *ALMA Development Study* proposal submitted in 09/2019 call (revised version in May 2020; PI Ondrejov), waiting for decision.
- Further considered capabilities: Spectral observations (FDM), sub-arrays, regional TP scans – some already started to be investigated, some are just wishes of solar-research community (no other group is interested, so hard to implement)
- Very inofficial: Early consideration of making joint proposals for ALMA & other large observatories (it is a question, whether the large solar telescopes might be included later).

Life-cycle of ALMA observation project: Data flow and SW



Life-cycle of ALMA observation project: A long-scale timing

- Phase I – proposal submission: Mid April (yearly)
- Evaluation of proposals: (end of) June (APRC meeting) – (mid) August (results released). Planned change (2022+): Peer review
- Phase II – SB approval by PI: September
- Scheduling, SB finalization & Observations: **Depending on the array configuration schedule!** (next slide)
- (Processed & QA2 “certified”) Data delivery: ~Two weeks after observation (sometimes later in case of issues)

Life-cycle of ALMA observation project:
Array config – the most severe constraint!

Complete Cycle 7 Configuration Schedule

Start date	Config	min - max baseline (m)	beam (")[1]	maximum recoverable scale (")[1]
2019-10-01	C43-4	15-784	0.92"	11.2"
2019-10-20	C43-3	15-500	1.4"	16.2"
2019-11-10	C43-2	15-314	2.3"	22.6"
2019-11-30	C43-1	15-161	3.4"	29.0
2019-12-20	C43-2	15-314	2.3"	22.6"
2020-01-10	C43-3	15-500	1.4"	16.2"
2020-02-01	February Maintenance Period			
2020-03-01	C43-4	15-784	0.92"	11.2"
2020-03-20	C43-5	15-1400	0.54"	6.7"
2020-04-24	C43-6	15-2500	0.31"	4.1"
2020-05-27	C43-7	64-3600	0.21"	2.6"
2020-06-20	C43-8	110-8500	0.096"	1.4"
2020-07-11	C43-9	368-13900	0.057"	0.81"
2020-07-30	C43-10	244-16200	0.042"	0.50"
2020-08-20	C43-9	368-13900	0.057"	0.81"
2020-09-10	C43-8	110-8500	0.096"	1.4"

Cycle 8

Start date	Configuration	Longest baseline	LST: Best conditions
1-Oct-20	C-8	8.5 km	22-10
20-Oct-20	C-7	3.6 km	23-11
10-Nov-20	C-6	2.5 km	1-13
1-Dec-20	C-5	1.4 km	2-14
20-Dec-20	C-4	0.78 km	4-15
10-Jan-21	C-3	0.50 km	5-17
1-Feb-21	No observations due to maintenance		
1-Mar-21	C-1	0.16 km	8-21
26-Mar-21	C-2	0.31 km	9-23
20-Apr-21	C-3	0.50 km	11-0
10-May-21	C-4	0.78 km	12-2
31-May-21	C-5	1.4 km	13-4
23-Jun-21	C-6	2.5 km	15-6
28-Jul-21	C-5	1.4 km	17-7
18-Aug-21	C-4	0.78 km	19-8
10-Sep-21	C-3	0.50 km	20-9

Life-cycle of ALMA observation project: A middle-scale timing

- Solar ALMA observations usually held in a campaign mode (dedicated time interval ~4 weeks, usually split into two parts)
- Detailed schedule prepared together by ARCs: EU (Miro Barta), NA (Tim Bastian), and EA (Masumi Shimojo). Finally approved by JAO (see an example at the next slide).
- The first draft of the schedule is prepared by the nature of science goals and reasonable mid-term solar activity forecast.
- **The PIs are requested** to stay in touch with their CS via *ALMA Helpdesk* and **express their wishes and constraints** given by requirements for coordinated observations.

Life-cycle of ALMA observation project: A middle-scale timing

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SolObsSched_Cycle5_2018r7

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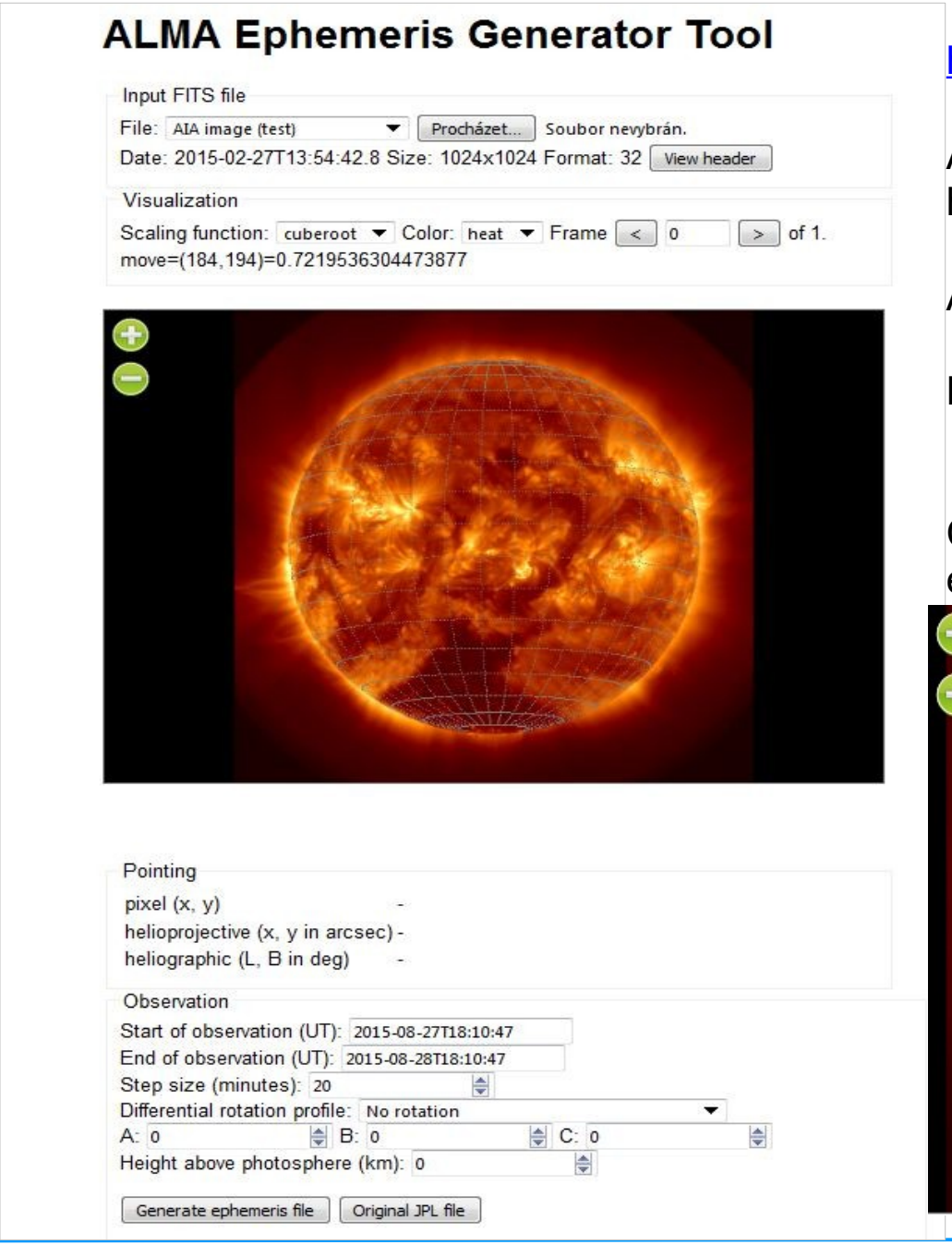
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Date		Start(UT)	End(UT)	indow (h	Config	SB	PI	CS	ative Ra	APRC Rank	Project	Objective		Grade	SB Name	AoD Lead	Status	
2	1/4/2018	Sun	13:44:00	19:24:00	5.68	C43-3	2h B3M	Shimojo	Shimojo	1	17	2017.1.00072.S	Polar CH		A	Sun_10_a_03_INT		Pass	Please start at ~1325
3							2h B3M									Sun_10_a_03_INT		Pass	
4	3/4/2018	Tue	13:45:00	19:21:00	5.62	C43-3	2h B3M	Shimojo	Shimojo	1	17	2017.1.00072.S	Polar CH		A	Sun_10_a_03_INT		Pass	Please start at ~1325
5							2h B3M									Sun_10_a_03_INT		Pass	
6	4/4/2018	Wed	13:46:00	16:00:00	2.23	C43-3	1h B3M	Leenarts	Barta	1'	8 (at Cycle	2016.1.00298.S	AR		A	Sun_10_a_03_INT		Semi-pass	Only 10 mins on targ
7							1.5h B6M									Sun_10_a_06_INT		Pass	
8	5/4/2018	Thu	13:47:00	19:18:00	5.53	C43-3	2h B3M	Okamoto	Shimojo	4	189	2017.1.00009.S	Prom		B				
9							2h B3M												
10	7/4/2018	Sat	13:49:00	16:00:00	2.18	C43-3	2h B6M	Peter		3	172	2017.1.01059.S	Em AR		B	Sun_10_a_06_INT		Not Observed	Please start at ~1330
11	8/4/2018	Sun	13:50:00	19:14:00	5.42	C43-3	2h B3M	Okamoto	Shimojo	4	189	2017.1.00009.S	Prom		B			Pass	
12							2h B3M											Pass	
13	10/4/2018	Tue	13:51:00	19:11:00	5.35	C43-3	2.5 B3S	Chen	Bastian	6	222	2017.1.01672.S	Spot		B	Sun_Band_a_03_INT		Not Observed	Please start at ~1330
14							1.2 B6S									Sun_Band_a_06_INT		Not Observed	
15							0.7h B6S									Sun_Band_b_06_INT		Not Observed	
16							0.7h B6S									Sun_Band_c_06_INT		Not Observed	
17	11/4/2018	Wed	13:52:00	16:00:00	2.13	C43-3	2h B6S	Okamoto	Shimojo/Kim	4			Prom			Sun_10_b_03_INT	Juan Cortes	Not Observed	
18	12/4/2018	Thu	13:53:00	19:08:00	5.27	C43-3	1.9h B6S	Nindos	Barta	2	154	2017.1.00653.S	QS		B	Sun_10_a_06_INT	Juan Cortes	Pass	Please start at ~1335
19							1.9h B3S									Sun_10_a_03_INT	Juan Cortes	Pass	
20	14/4/2018	Sat	15:00:00	16:00:00	1	C43-3											Juan Cortes		VLBI ends at 15 UT
21							1.3h B3S									Sun_10_a_03_INT			
22	17/4/2018	Tue	15:00:00	19:00:00	4	C43-3	2h B6S	Labrosse	Barta/Berlicki	7	239	2017.1.01138.S	Prom		B	Sun_10_a_06_INT	Juan Cortes	Pass	VLBI ends at 15 UT
23							2h B3S									Sun_10_b_03_INT	Juan Cortes	Pass	
24							1h B3M									Sun_10_a_03_INT	Juan Cortes	Pass	
25	19/4/2018	Thu	14:01:00	18:57:00	4.95	C43-3	2h B3M	Labrosse	Barta/Berlicki	7	239	2017.1.01138.S	Prom		B	Sun_10_a_03_INT	Bill Dent	Pass	
26							1h B3S									Sun_10_b_03_INT	Bill Dent	Pass	
27	21/4/2018	Sat	14:03:00	16:00:00	2		2h B6	Okamoto	Shimojo			2017.1.00009.S				Sun_10_b_06_INT		Pass	
28	24/4/2018	Tue	14:06:00	18:50:00	4.75	C43-3	1h B3M	Leenaarts	Barta/Murato	1'								Not Observed	
29							1.5h B6M											Not Observed	
30	26/4/2018	Thu	14:09:00	18:46:00	4.63	C43-3	2.5h B3S	Chen	Bastian	6		2017.1.01672.S	AR		B	Sun_Band_a_03_IN	I. Toledo	Pass	
31	28/4/2018	Sat	14:11:00	16:00:00	1.82	C43-3													
32	29/4/2018	Sun	14:13:00	18:42:00	4.5	C43-3	1.5h B6M	Leenaarts	Barta/Murato	1'		2016.1.00298.S	AR		B	Sun_10_a_06_INT	I. Toledo	Pass	
33							1 h B3M									Sun_10_a_03_INT	I. Toledo	Pass	
34	5/1/2018	Tue	14:15:00	18:39:00	4.42	C43-3	2h B6M	Antolin	Barta/Murato	5	195	2017.1.00870.S	Limb AR			Sun_10_b_06_INT	I. Toledo	Pass	
35							2h B3M									Sun_10_b_03_INT	I. Toledo	Pass	

Life-cycle of ALMA observation project: A short-scale timing

- A couple of days the PI submits the Target of Opportunity (ToO) ticket and adds (later, 2days before obs. actually happens) the observation details there (e.g., HPC coordinates/target-tracking info/ephemeris – see the next slide, dimensions/shape/PA of the FoV, back-to-back SBs -Y/N,...)
- The ToO ticket stays open during entire preparation phase up to successful observation is completed. The ALMA AoDs + Hinode and IRIS coordinators are automatically included into this communication.
- Things to take into account on the day/hours scale:
  - ALMA AOS is 67.7W, 23S → local ALMA time = UT – 4.5 hour, seasons are opposite then in Europe.
  - Sun's elevation must be between 40 and 70 degs.
  - The weather (PWV) tends to worsen with (local) time – high-frequency obs. better to be done in local morning.
  - Should the TP observations are critical for you, avoid windy periods (see the weather stats at ALMA website)

Life-cycle of ALMA observation project: An ultrashort-scale timing – tracking the target



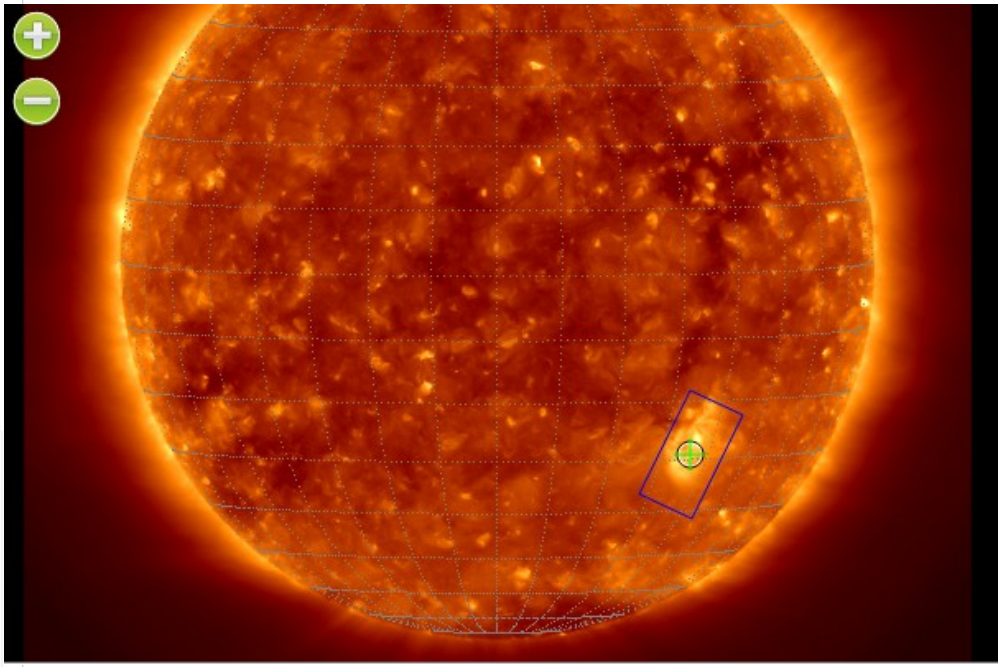
http://celestialscenes.com/alma/coords/CoordTool.html

Accessible from *ALMA Science Portal*
http://www.almascience.org

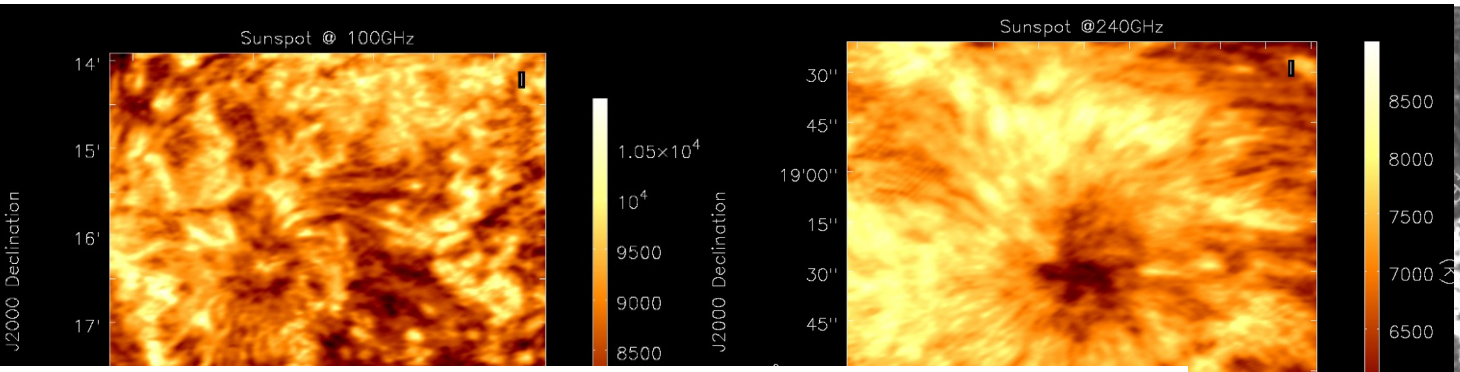
Author: **Ivica Skokic**

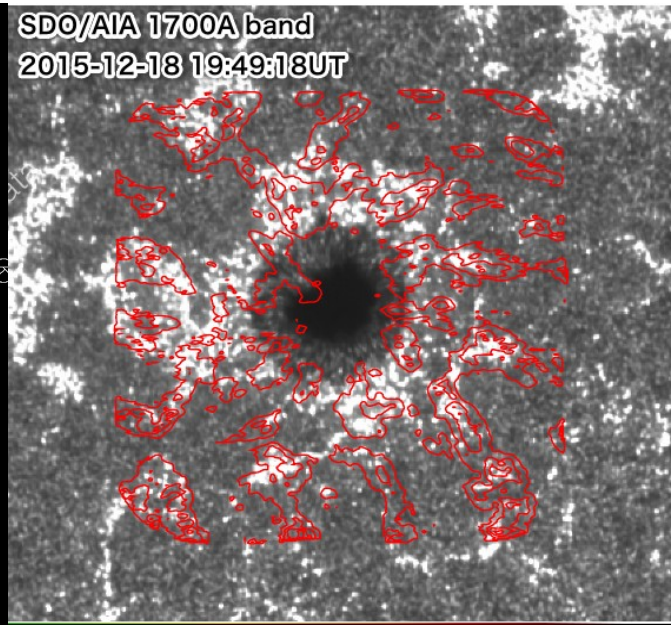
Nowadays used for (E)VLA and other observatories, too.

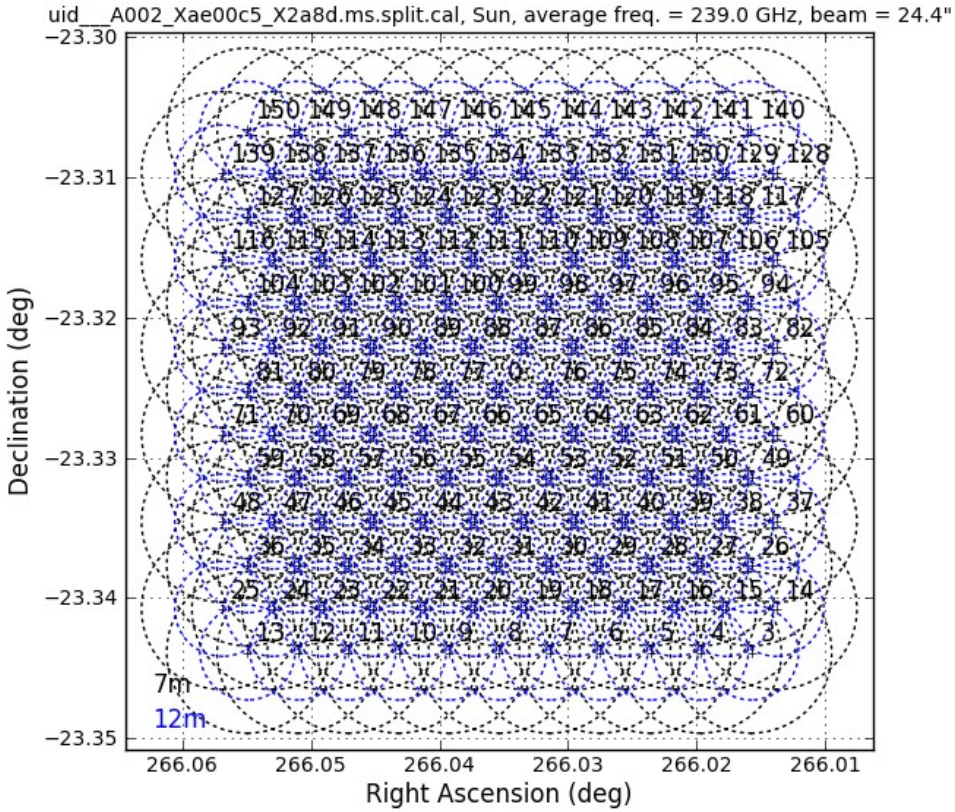
Choose the FoV and tracking info, then generate the ephemeris.



Life-cycle of ALMA observation project: An ultrashort-scale timing – tracking the target







This sunspot Band 6 image is a mosaic
Of ~150 pointings, each takes 7.5 s

FoV for SP is ~25”

Co-ordinated observations with ALMA – existing examples

- Co-ordination with Hinode and Iris works **automatically** – these instruments adapt to the ALMA targets. The target and tracking info has to be submitted via ALMA ToO ~2 days prior the observation starts. Basically all solar ALMA observing projects received successfully the space-born coordinated observations.
- It is possible to plan coordinated observations with PSP – not automated, PI must apply for time at PSP
- Coordinated observations ALMA + Hinode + SDO + **ground-based optical telescopes** exist, too – in Europe we have a working example:

  ALMA project Cy6 2018.1.01518.S, *Heating in small-scale explosive events in the chromosphere*, PI Joao Manuel da Silva Santos, **SST included**. Observed in April 2019.

PI name	SB name	Proposal authors	Line sens. (10 km/s)	PWV	Group ous id	Member ous id	Asdm uid	Project title	Type	Scan intent	QA2 Status
Santos			mJy/beam	mm							
da Silva Santos, Joã...	Sun_10_a_03_INT	Vissers, Gregal; Leen...	0.62	0.50	uid://A001/X133d/X3239	uid://A001/X133d/X323a	uid://A002/Xdab261/X130...	Heating in small-scale e...	S	TARGET	PASS
da Silva Santos, Joã...	Sun_10_a_06_INT	Vissers, Gregal; Leen...	1.75	0.41	uid://A001/X133d/X3233	uid://A001/X133d/X3234	uid://A002/Xdab261/X11f...	Heating in small-scale e...	S	TARGET	PASS
da Silva Santos, Joã...	Sun_10_a_03_TP	Vissers, Gregal; Leen...	45.17	5.19	uid://A001/X133d/X3239	uid://A001/X133d/X323c	uid://A002/Xdab261/X131...	Heating in small-scale e...	S	TARGET	PASS
da Silva Santos, Joã...	Sun_10_a_06_TP	Vissers, Gregal; Leen...	29.83	1.80	uid://A001/X133d/X3233	uid://A001/X133d/X3236	uid://A002/Xdab261/X120...	Heating in small-scale e...	S	TARGET	PASS

Summary

- **ALMA has very hard/unavoidable constraints** for solar observations, especially **timing on the scale of months** related to appropriate array configuration – you have to try to adapt your co-observations to this constraints.
- **Local time at AOS is UT – 4.5h**, seasons are reverted to Europe – take this into account when planning coordinated observations. The elevation of the Sun at AOS must be 40 – 70 degs.
- Short time-scale coordination happens on the scale weeks/days and takes place over ALMA ToO ticket. Please, keep your CS informed about your plans concerning the coordinated observations (via ALMA Helpdesk)!
- Hinode and SDO/AIA make overtake the ALMA solar targets automatically, keep the instrument observers informed via the ALMA ToO, deadline is ~2days before observations.
- **Coordination with European telescopes is more demanding** (reverted seasons, local time-lag,…) **but not impossible** we have a nice working example (ALMA + SST + Hinode) from Cycle 6.
- Future (ALMA) development may relax some constraints (more extended configurations for Solar ObsMode, easier joint proposal).
- **Covid-19 has caused (at least) 1 year gap in ALMA observations.**