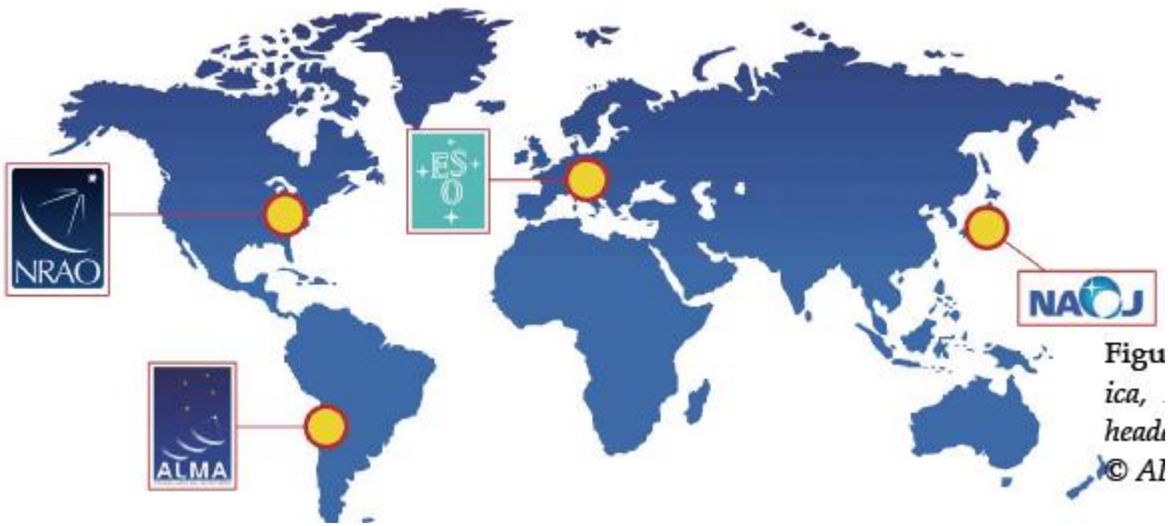
ALMA: результаты тестовых наблюдений Солнца и перспективы наблюдений в четвертом цикле

Лукичева Мария Александровна

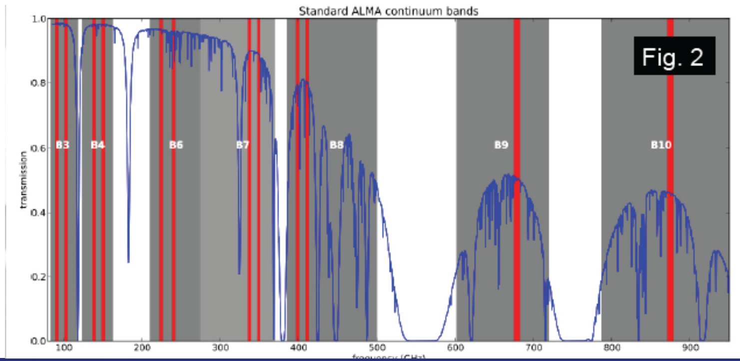
СПбГУ

ALMA Organization

ALMA is a partnership between North America, Europe, and East Asia in cooperation with the Republic of Chile. ALMA construction and operations are led on behalf of Europe by the European Organization for Astronomical Research in the Southern Hemisphere (**ESO**), on behalf of North America by the National Radio Astronomy Observatory (**NRAO**), which is managed by Associated Universities, Inc. (AUI), and on behalf of East Asia by the National Astronomical Observatory of Japan (**NAOJ**). The Joint ALMA Observatory (**JAO**), located in Santiago, Chile, provides the unified leadership and management of the construction, commissioning and operation of ALMA.



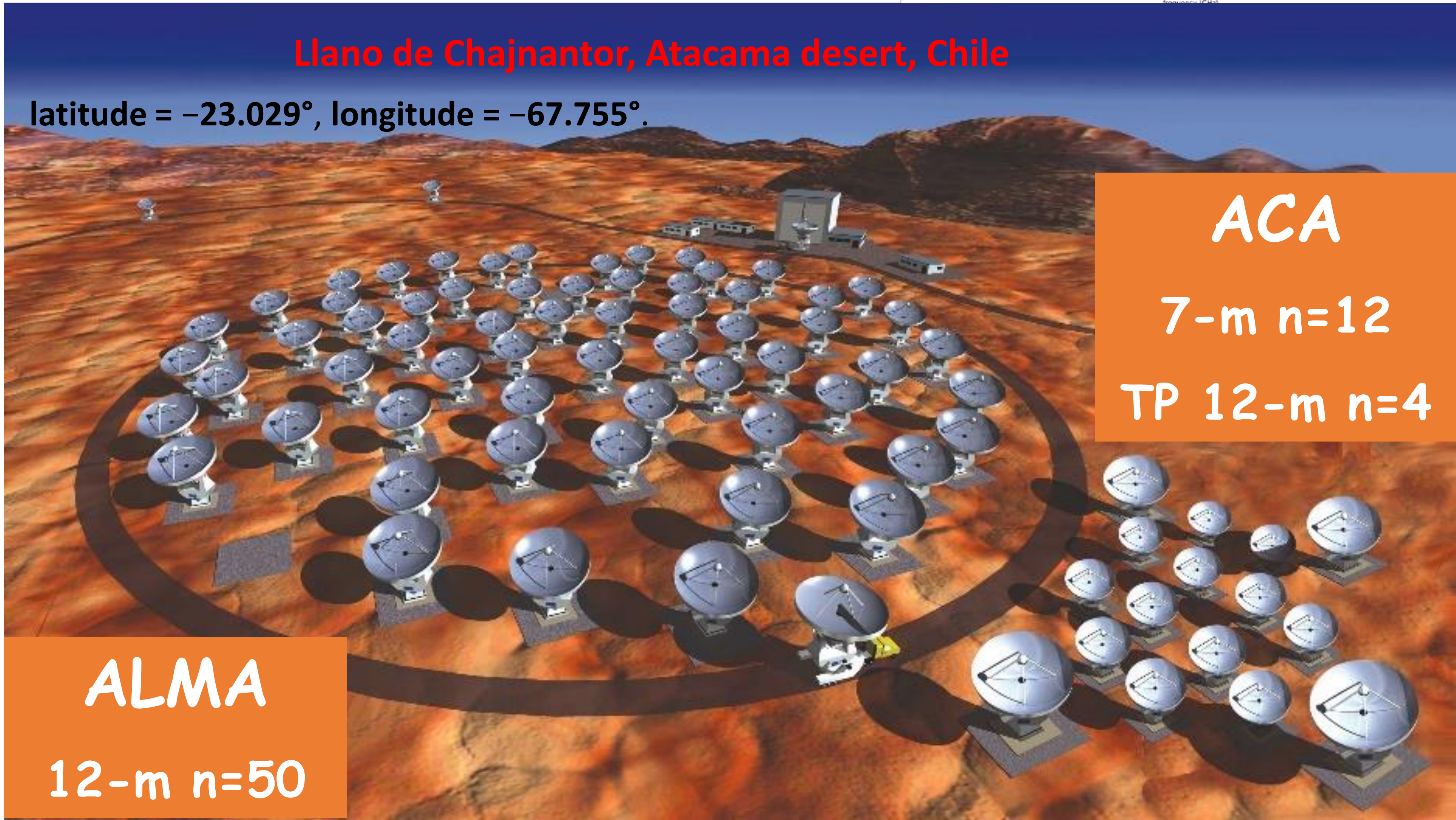
ALMA+ACA = Atacama Large Millimeter/Submillimeter Array



- ►ALMA = 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)



The Atacama Large Millimeter Array (ALMA) Quick Reference

- **Early 2011**: Call for ALMA Early Science Proposals
- **Mid 2011**: Early Science Proposal submission deadline
- **Late 2011**: Early Science begins
- **2013**: 66 ALMA Antennas

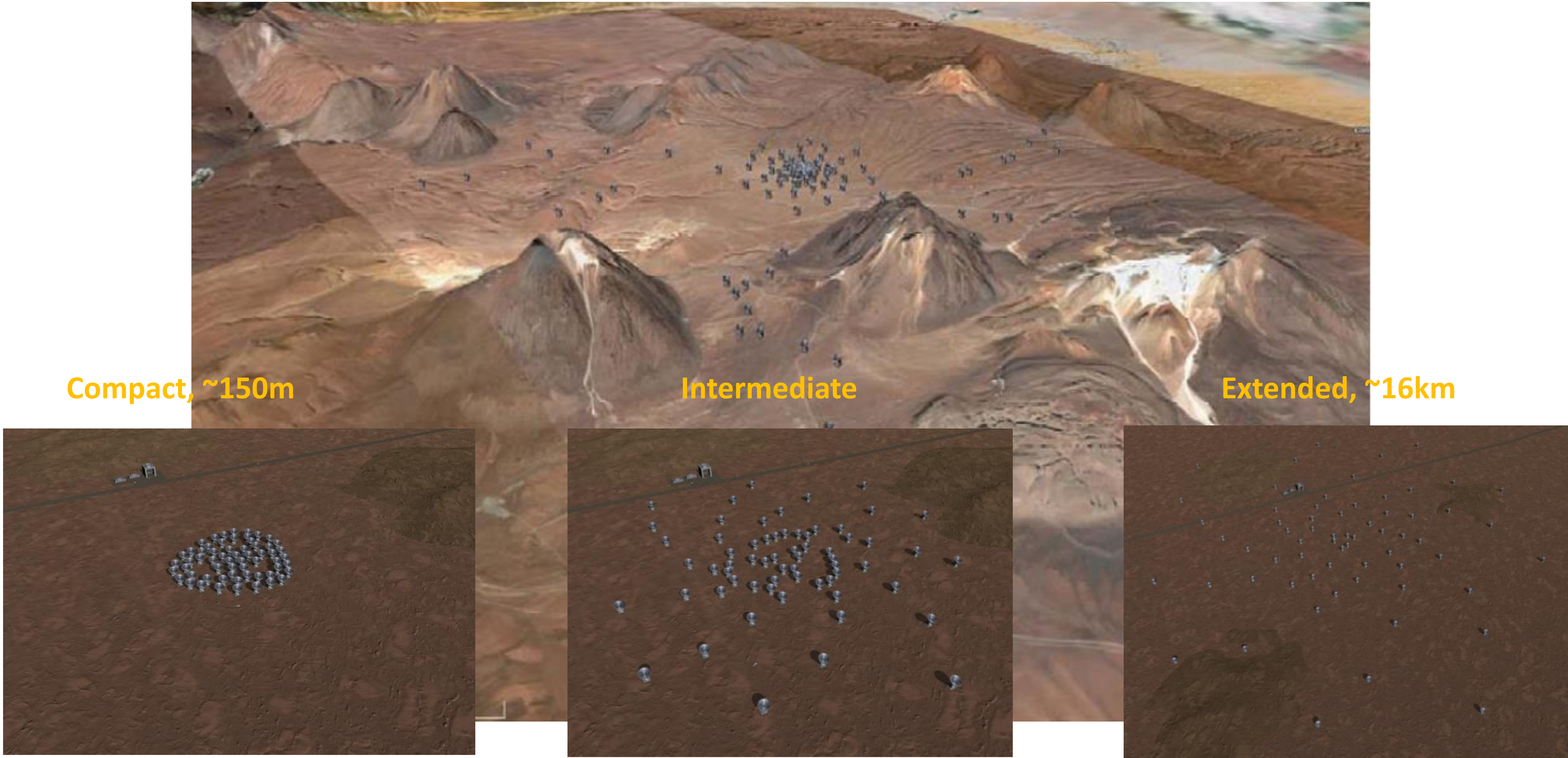
Bands:	3	4	5	6	7	8	9	10
Frequency (GHz)	84-116	125-163	163-211	211-275	275-373	385-500	602-720	787-950
Wavelength (mm)	3.57-2.59	2.40-1.84	1.84-1.42	1.42-1.09	1.09-0.80	0.78-0.60	0.50-0.42	0.38-0.32

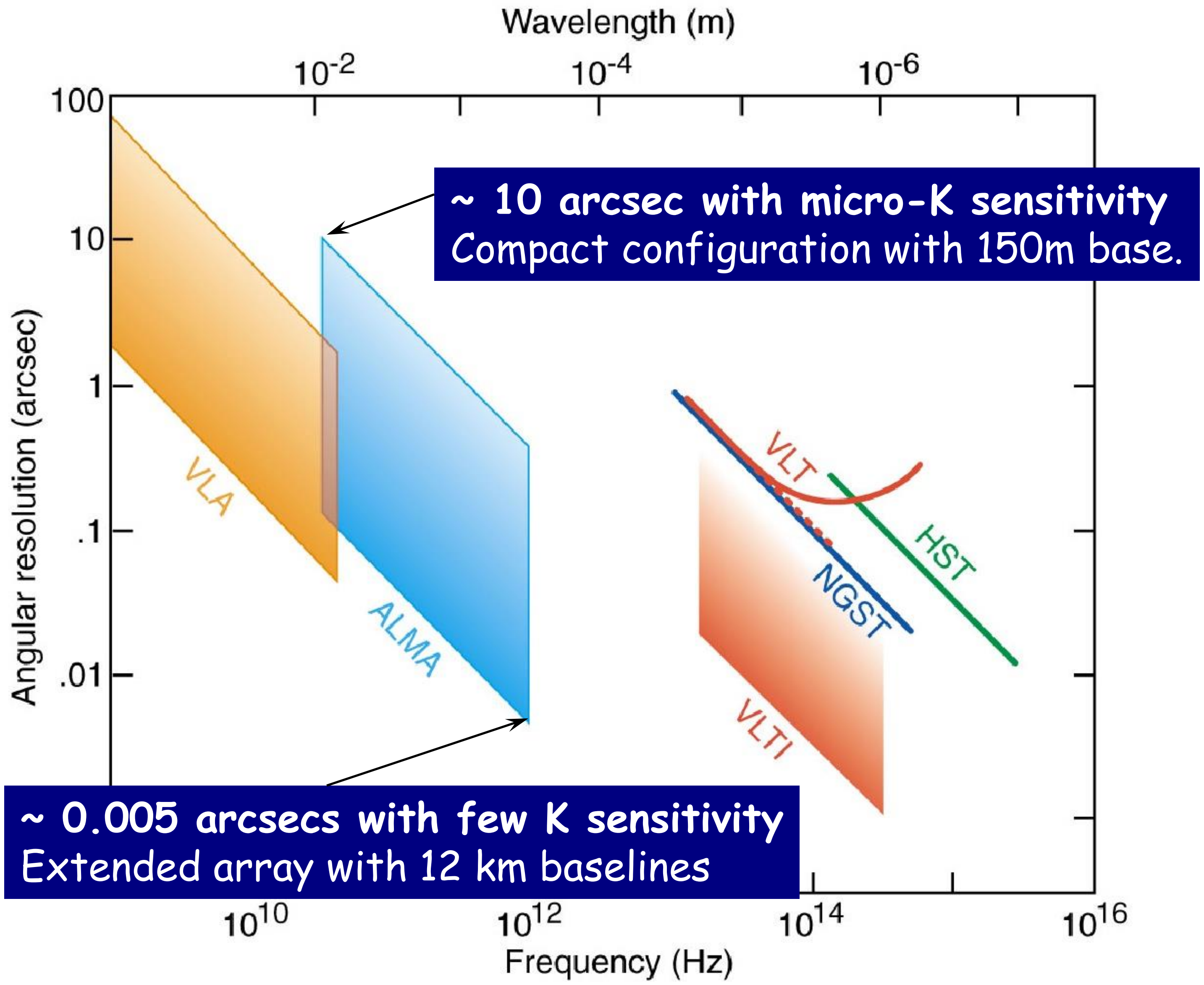
	Early Science	Array Completion
Antennas	≥16 x 12m	At least 54 x 12m & 12 x 7m
Bands	Bands 3, 6, 7, 9	Bands 3, 4, 6, 7, 8, 9 & 10
Maximum Bandwidth	16 GHz (2 polarizations x 8 GHz)	
Correlator Configurations	21 (0.02 – 40 km/s)	71 (0.01 – 40 km/s)
Maximum Angular Resolution	$0.02'' \left(\frac{\lambda}{1\text{ mm}}\right)\left(\frac{10\text{ km}}{\text{Max Baseline}}\right)$	
Max Baseline	250m (may achieve 500m)	15 km
Continuum Sensitivity (60 sec, Bands 3–9)	~0.2 – 4.2 mJy	~0.05 – 1 mJy
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3–9)	~30 – 250 mJy	~ 7 – 62 mJy

Sensitivity Calculator: http://science .nrao.edu/alma/tools.html

- ► Very high spatial resolution (up to 0.005“ in extended configuration@ 1THz)
- ►Extremely high spectral resolution–up to 30kHz
- ►Temporal resolution for very bright sources (e.g. the Sun) ~ 1s
- ►Very high sensitivity

View of site with antennas in the most extended configuration :
185 Pads - baselines up to 16km





Wavelength (m)
10-2
10-4
10-6
100
10
1
.1
.01
Angular resolution (arcsec)
VLA
ALMA
VLT
HST
NGST
VLTI
10^10
10^12
10^14
10^16
Frequency (Hz)
~ 10 arcsec with micro-K sensitivity
Compact configuration with 150m base.
~ 0.005 arcsecs with few K sensitivity
Extended array with 12 km baselines

ALMA: scientific goals

ALMA is not a specialized telescope,

but very well suited to some domains:

– High-Z universe

– Structure and evolution of galaxies

– Stellar formation and evolution

– Planetary system formation

– Interstellar chemistry (from galaxies to protoplanetary disks)

– Solar System and the Sun

ALMA: observing the Sun

Solar peculiarities: Why the solar observations need special treatment?

The Sun is **far brighter** in mm/sub-mm than other mm sources

Issue of dynamic range (e.g., in comparison with **calibrators**)

Variability on short timescales (down to <1s in solar flares)→ just **instantaneous** *uv* coverage

In addition to apparent celestial motion of the Sun‘s center also (differential) solar rotation → **complicated pointings** (specific ephemeris)

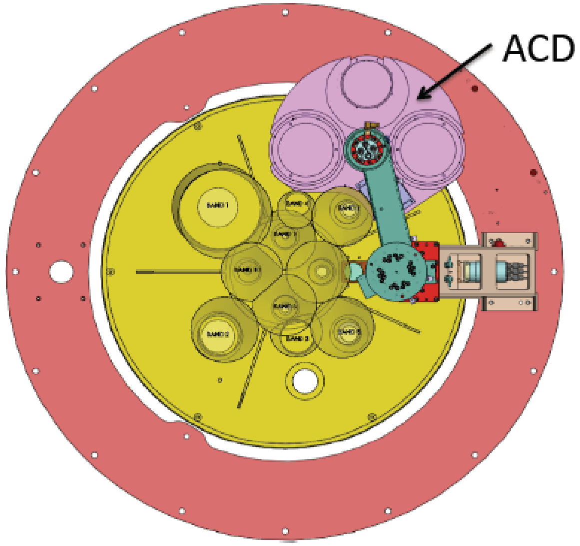
Specific coordinate systems used in solar physics

(usually) **Extended sources** –TP mapping needed in a fast-scanning mode

Solar Filter

Disadvantages to the SFs

- Flux calibration complicated
- SNR greatly reduced on calibrators
  - Also noise added by SF
- SF introduces frequency dependent variation in the complex gain
- SF introduces wave front errors that distorts beam shape & adds sidelobes
- WVRs blocked by ACD in many bands with SF



- Possibility of solar observing was incorporated in the design from the beginning
- Requires a dish surface that scatters the near-infra-red out of the beam – roughen or scallop the surface (tens of microns scale)
- Requires additional attenuation to get the signal down to the level that the system is designed to operate at (solar filters) The flux calibration of the images is impossible because we cannot use the calibration device located in the antenna when we use the solar filters. Large time overhead. measurements of phase delays practically unreproducible
- Alternative strategy to challenge the large flux density: the system gain can be reduced by electronically ”de-tuning” the front end (MD modes).

Solar ALMA Science

- Chromospheric thermal and magnetic structure
- Chromospheric dynamics: waves, shocks, reconnection, chromospheric heating
- Filaments, sunspots, prominences, spicules, seismology, etc.
- Synchrotron emission of small flares: coronal heating
- Chromospheric reaction to coronal flares
- Lines emission: recombination lines, Zeeman effect, molecular lines ?

Solar Alma Science Review Paper Wedemeyer at al. (2015) a peer-reviewed paper (with 38 authors) highlighting ALMA science – published in 2015 in Space Science Reviews

Potential solar science cases for ALMA

Solar Alma Science Review Paper Wedemeyer at al. (2015)

Quiet Sun regions:

1. The thermal structure and dynamics of Quiet Sun regions
2. Numerical predictions of quiet Sun ALMA observations
3. Magnetic fields in Quiet Sun regions
4. Vortex flows
5. Polar brightenings

Spectroscopic study of recombination lines and molecules:

1. Rydberg transitions
2. Carbon monoxide

Active regions and sunspots:

1. Active region modelling and predictions for ALMA
2. Structure and dynamics of sunspot umbrae
3. Penumbral waves
4. Small-scale dynamic events in sunspot penumbrae
5. Ellerman Bombs
6. Explosive Events

Solar flares:

1. Major events
2. Microflares and nanoflares
3. The lower atmosphere
4. Quasi-periodic pulsations
5. Particle beam heating of the chromosphere Triggering mechanism of subflares in active regions

Chromospheric heating in regions with strong magnetic field

Chromospheric oscillations and waves:

1. Wave propagation in the solar atmosphere Alfv´en waves
2. Resonant absorption and associated heating

Magnetic loops in the upper atmosphere:

1. Coronal rain
2. The fine-structure of coronal loops

Prominences

Implications for other fields of astrophysics:

1. Stellar flares
2. Magnetic vortices and the Sun as plasma laboratory

ALMA solar development programs

- Regular solar observations have not yet started because of the many technical challenges that must be addressed (the large radio flux density, short dynamical scales, calibration issues, source tracking, etc). These issues have to be resolved before the solar ALMA observing mode can be commissioned.
- In order to coordinate efforts addressing these issues and to enable ALMA's use by the broader international solar community, two development studies have been funded – the North American ALMA solar development program and the ESO ALMA solar development program. A major goal is to coordinate effort by the members of the international solar physics community to develop recommendations and requirements for implementing an initial suite of solar observing modes for use by the wider community on ALMA in Cycle 4
- On September 1st, 2014, the Solar Simulations for the Atacama Large Millimeter Observatory Network (SSALMON) was initiated in connection with these two international ALMA development studies and in collaboration with the Czech node of the ALMA Regional Center. The main purpose of the network is to co-ordinate activities related to solar science with ALMA and to promote the scientific potential of ALMA observations of the Sun with particular focus on modeling aspect

- 6 solar CSV observing campaigns, 6th – Dec 2015
- Solar community workshop highlighting synergies between ALMA, the NSO DKIST O/IR telescope, the NASA IRIS UV mission, March 15-18, 2016, in Boulder

History of Solar Observations with ALMA (Band 3 receiver)

- **1st Solar Campaign (June 2011)**

Verified the tracking of solar structures using ephemeris files.

Obtained first filtering of the Sun with ALMA.

Based on the results, the change the attenuation level of the solar filters (-20 dB " -10 dB) is requested.

- **2nd Solar Campaign (December 2011)**

Developed the script for observations with solar filters.

Established the method of measuring the delay caused by a solar filter.

- **3rd Solar Campaign (June 2012)**

First observation of the Sun using a 7m-antenna.

Verified the stability of the pointing and focus during a solar observation.

Verified the stability of the delay caused by the solar filters.

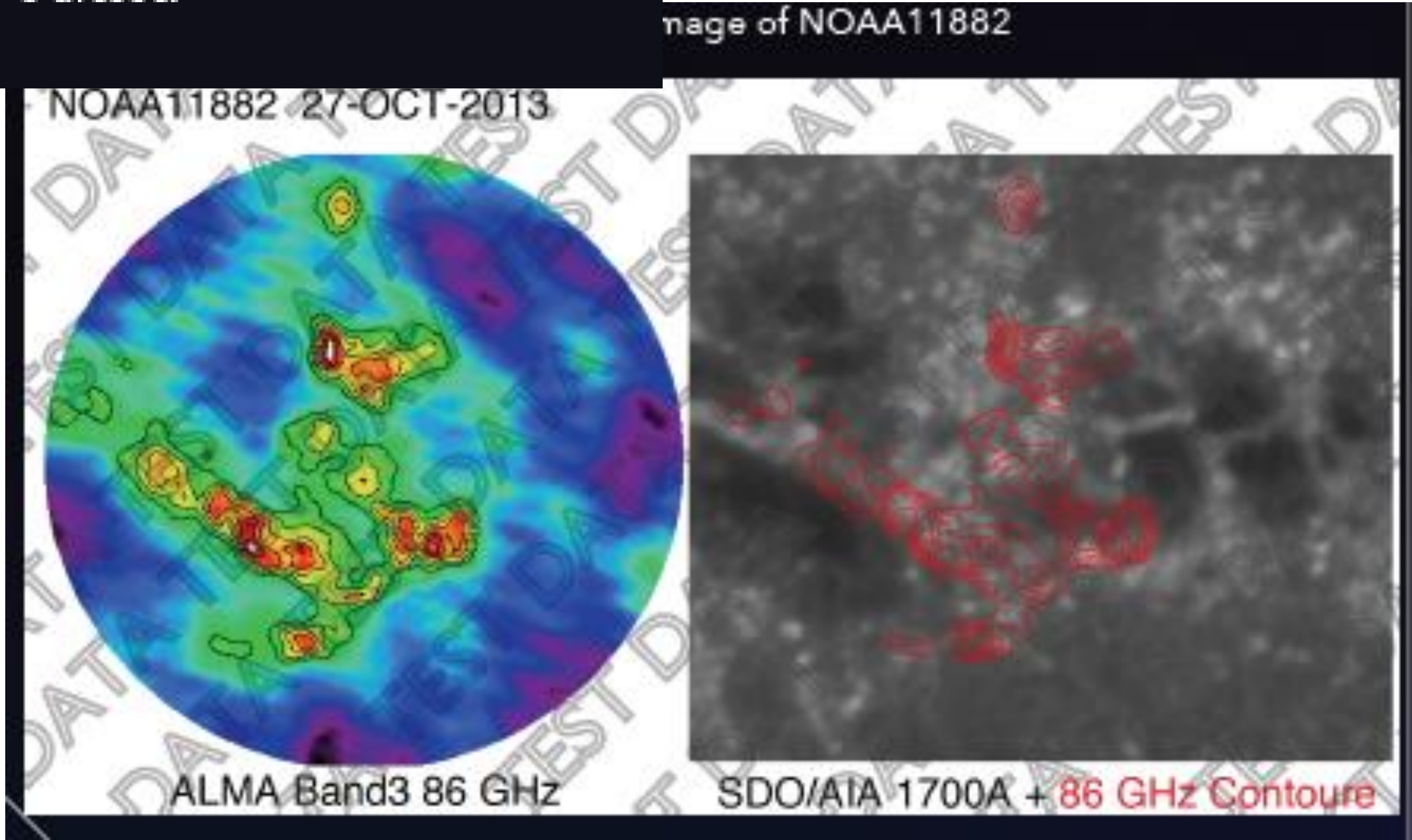
Established the simple observing sequence for solar interferometric observations with the solar filters.

- **4th Solar Campaign (October 2013)**

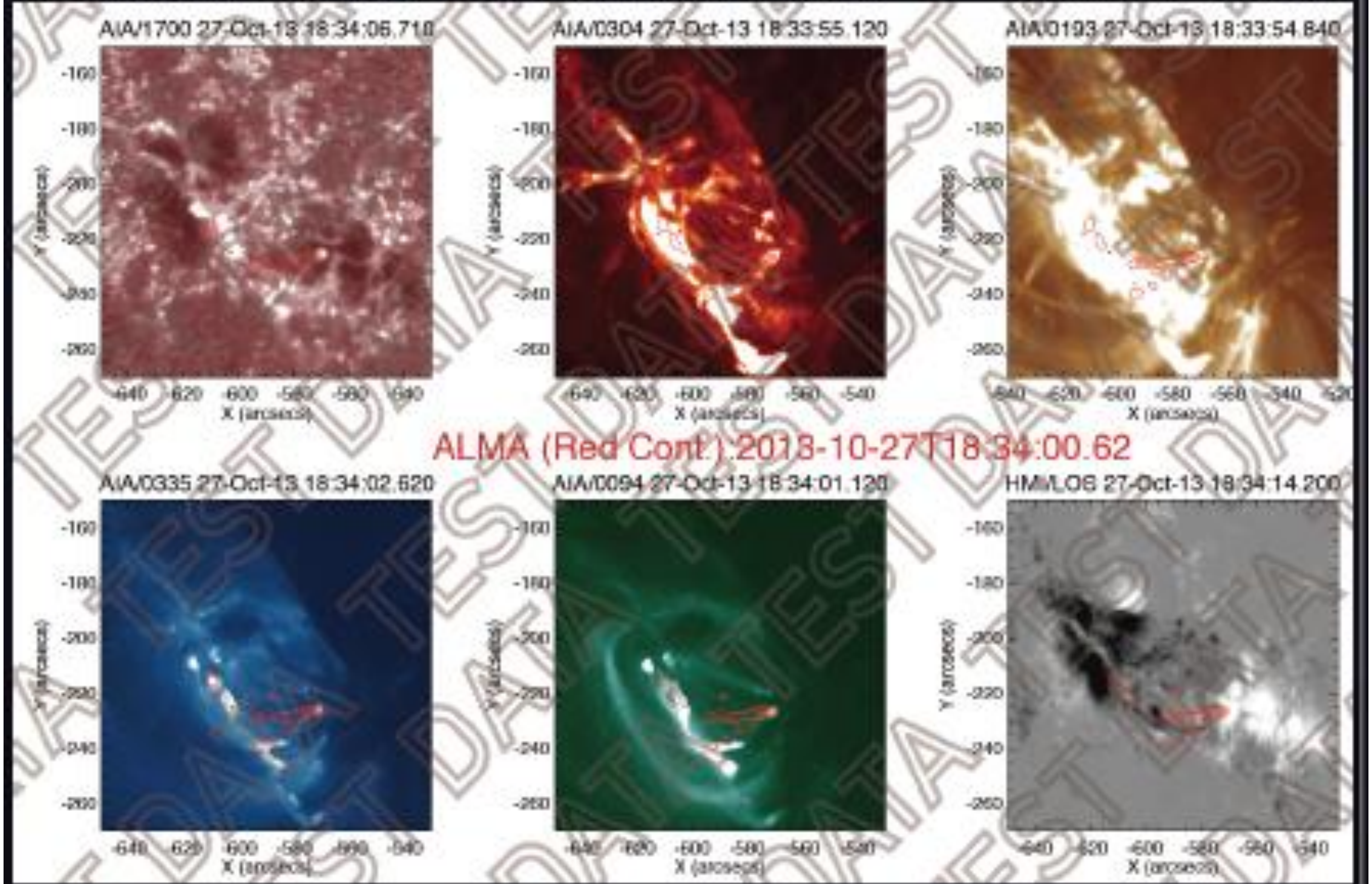
Succeeded in synthesizing the solar images from the visibility data obtained with the solar filters.

- **5th Solar Campaign (December 2014)**
- **6th Solar Campaign (December 2015)**

- Observation
  - Date: 27 October 2013 (4^{th} Solar Campaign)
  - Target: NOAA11882
  - # of antennas: 12m 9, 7m 7 = Total 16
  - Receiver: Band3
    - Center frequency of each spectrum window: 86.3 GHz, 88.2 GHz, 97.3 GHz, 99.2 GHz
    - When we observed the Sun, the solar filters were inserted above the receivers.
  - All antennas connected to the BL Correlator with Time Domain Mode.
  - The size of the synthesized beam is 2 ~ 3 arcsec.
    - The shape of the beam is an ellipse.



- Preliminary Result 1: The 86.3 GHz image of a C1-class flare
  - Integration Time: 1 second



5th Solar Campaign – 9-16 Dec 2014

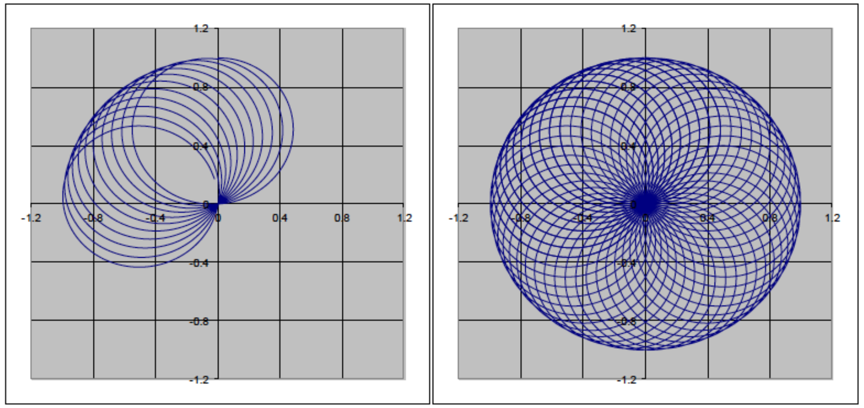
- 8 x 7m antennas and 30 x 12m antennas
- **Solar observations with the de-tuning SIS mixers in the campaign.** The method is that we reduce the sensitivity of the receiver by changing the bias voltage of the SIS mixer.
- Several targets: quiet Sun, active region, and quiet limb target
- A large sunspot, nearby plage, and a filament
- A coronal hole target, nearby quiet Sun, and a prominence target
- An active region target for flaring
- develop the script to time share between bands 3 and band 6
- "pseudo-mosaicking"; i.e., map a target as multiple sources and combine them linearly in post-processing

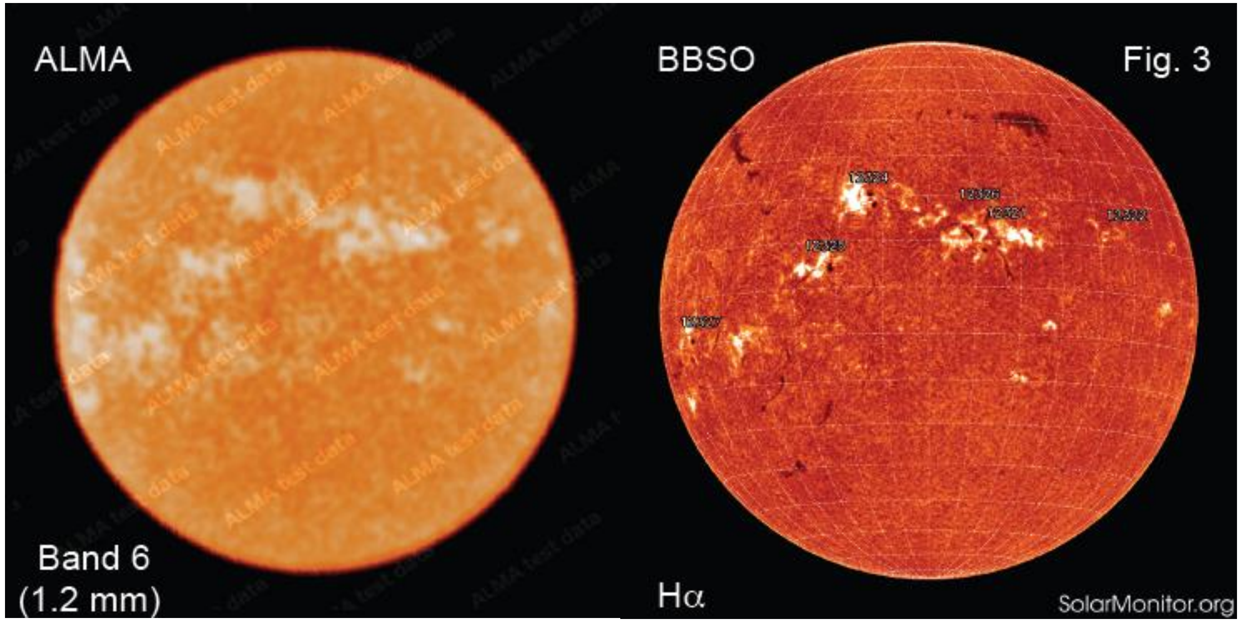
Test Data: Credits to Solar ALMA Development Teams

Single Dish Fast Mapping (Dec 2014)

Imaging with single-dishes: very fast, using several dishes, well advanced

Drive the antennas smoothly through continuous scan patterns: e.g. Lissajous or double circle. Use redundant crossings to calibrate out opacity variations . Maps of the Sun (2400x2400arcsec^2) are generated in 4—20 min, depending on the band





Resolution:
Band 3 **(3 mm): 60”**
Band 6 **(1.2 mm): 24”**
Band 7 **(0.9mm): 18”**
Band 9 (**0.4mm): 9”**

SD FM -

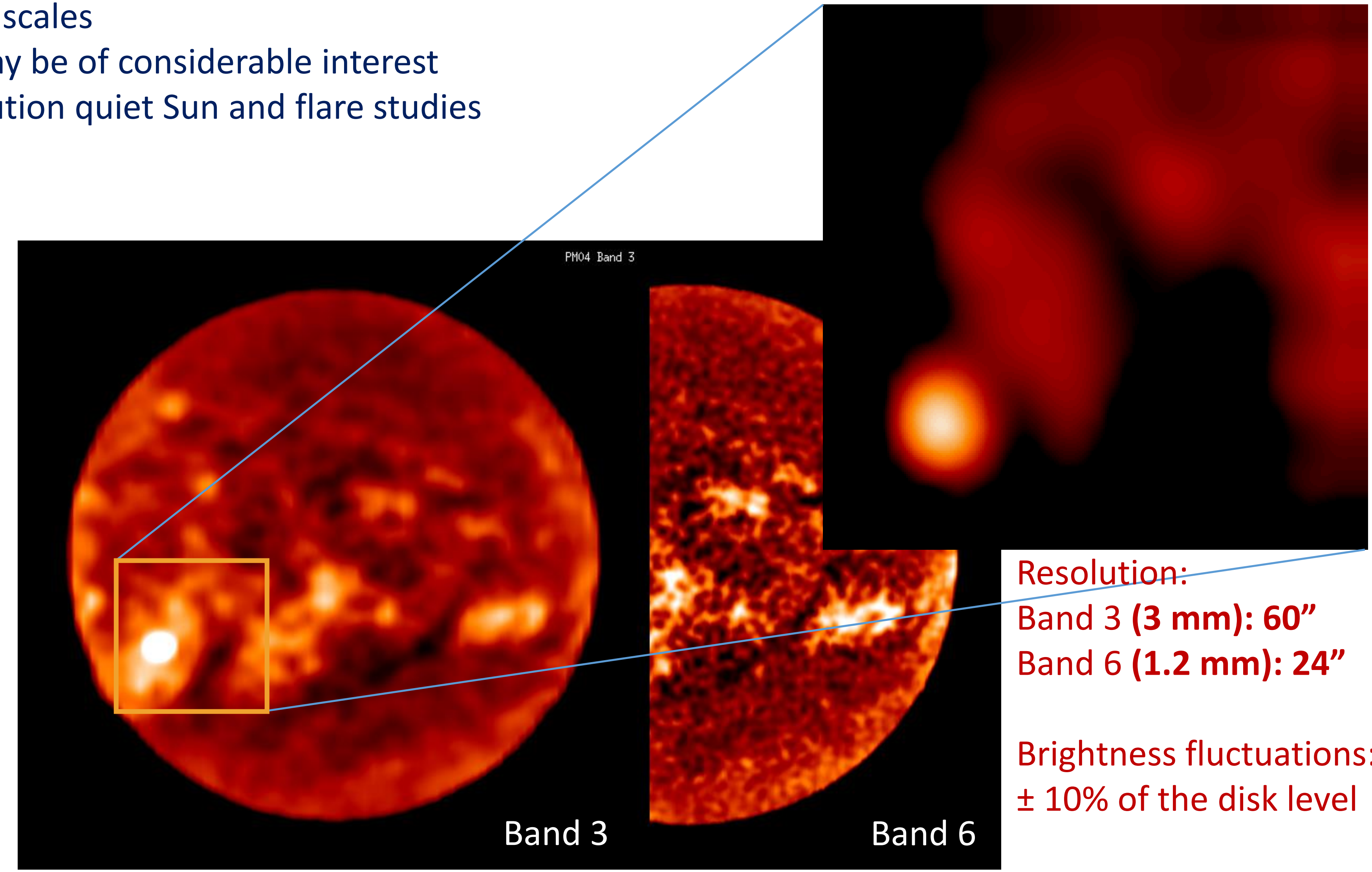
- Originally developed by R. Hills, N. Phillips, R. Marsdon, and colleagues
- Brightness calibration - S. White, K. Iwai, and colleagues

Test Data: Credits to Solar ALMA Development Teams

Single Dish Fast Mapping (Dec 2014)

- SD fast mapping critical for filling in flux on large angular scales
- The mode may be of considerable interest for low resolution quiet Sun and flare studies

The bright feature in the lower left of band 3 is the flare site. The quiet-Sun structure in the band 6 map at 20" resolution looks a lot like what was seen in 3 mm interferometer maps with CARMA and BIMA.



Resolution:
Band 3 **(3 mm): 60”**
Band 6 **(1.2 mm): 24”**

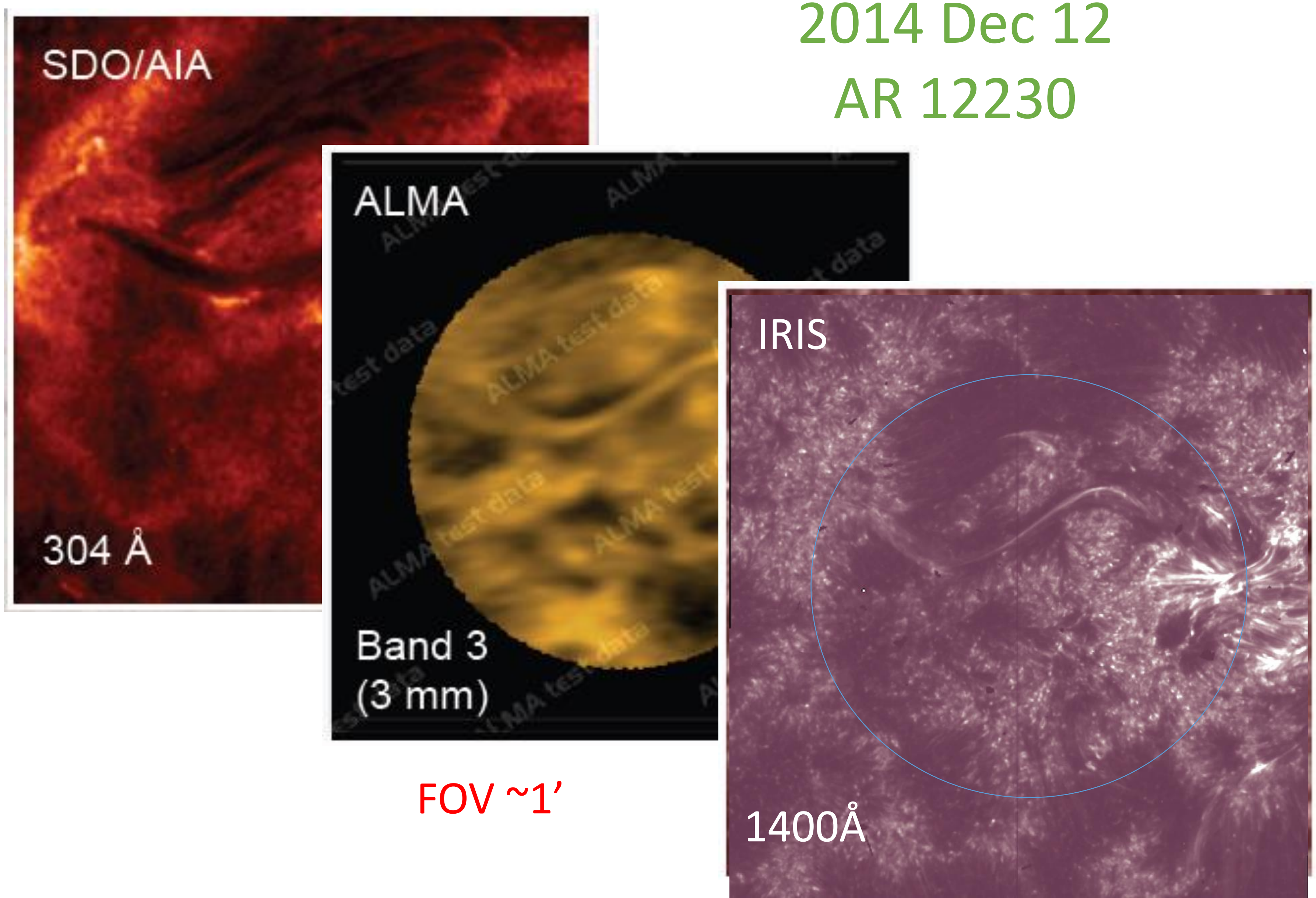
Brightness fluctuations:
± 10% of the disk level

Test Data: Credits to Solar ALMA Development Teams

ALMA Interferometric Mapping

2014 Dec 12

AR 12230



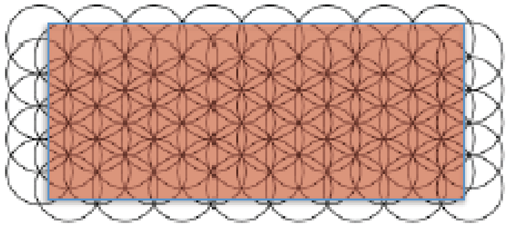
FOV ~1’

Mosaicing

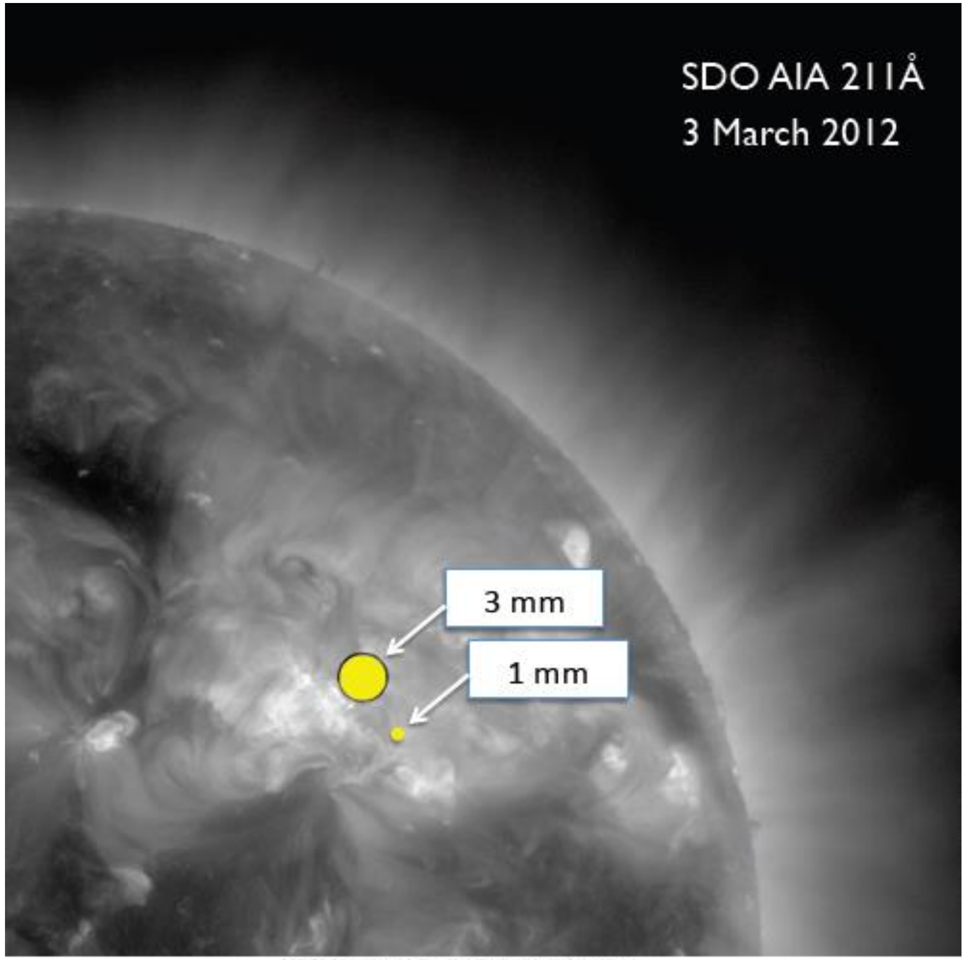
The ALMA field of view, determined by the primary beam of the 12 m antennas, is small: $\Theta_{FWHP} \approx 20''\lambda_{mm}$

- Many observing programs will need to perform mosaicing observations.
- The minimum number of pointings is determined by Nyquist sampling requirements and the size of the target field of interest. For example, to map a 1′ x 3′ field one needs:

Freq (GHz)	Rectangular	Hexagonal
86 (b3)	12	14
230 (b6)	70	80
350 (b7)	147	175
850 (b10)	867	1003



OTF mapping desirable



6th campaign – December 2015

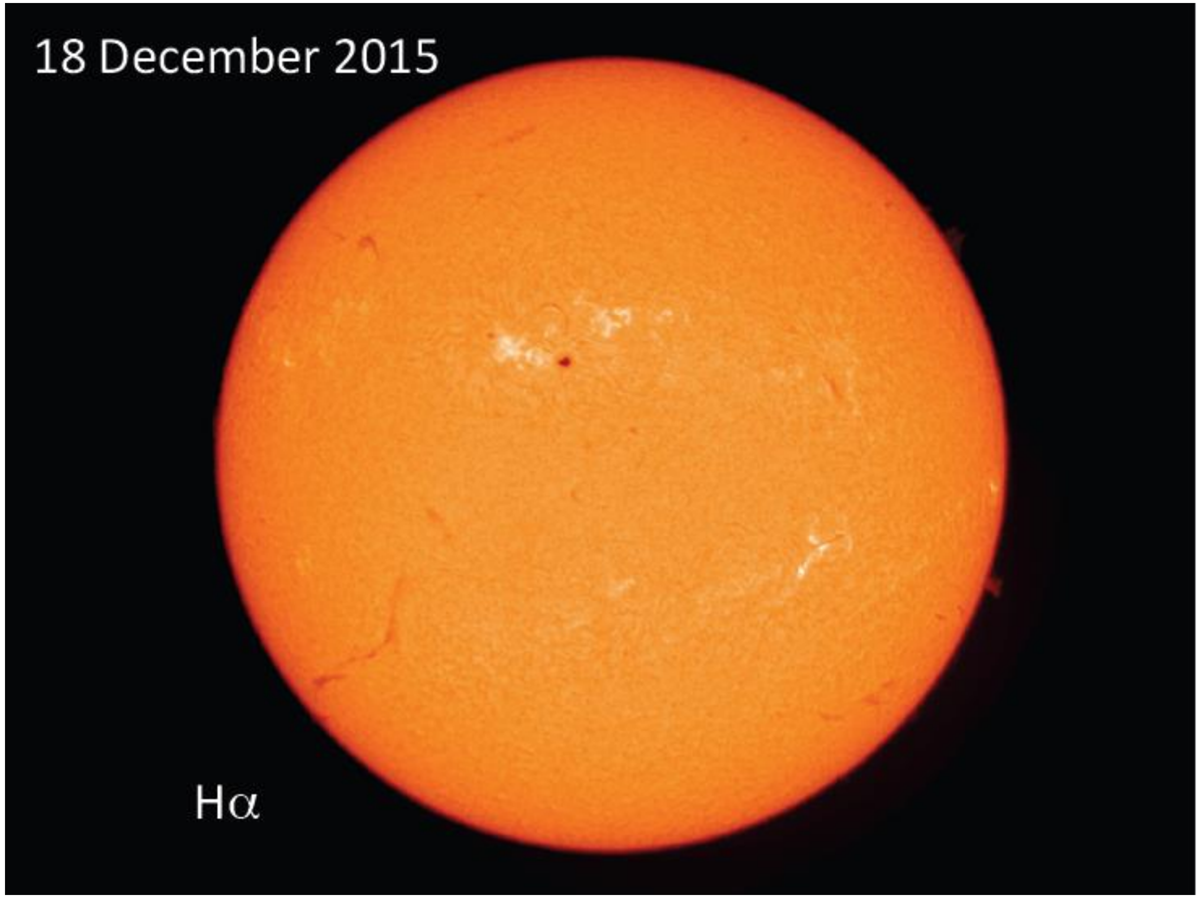
"Dress rehearsal"

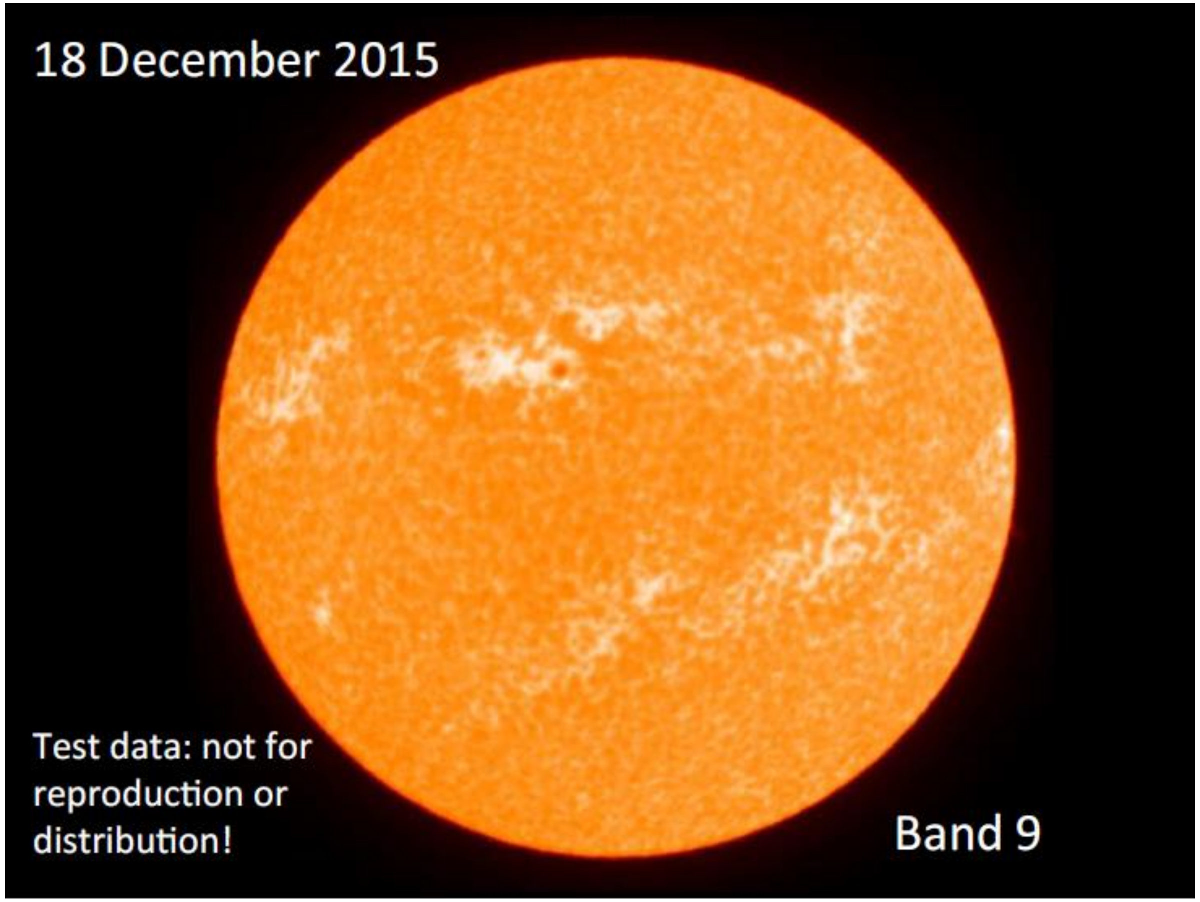
- For many science programs, a larger field of view is essential. Mosaicing is therefore required, plus TP mapping
- While the WVRs are accessible using MD modes, they saturate. We must confine ourselves to compact arrays for now

Development and testing during 2015 focused on:

- mosaicing and total power mapping,
- working out calibration,
- development of SBs,
- reduction and imaging scripts

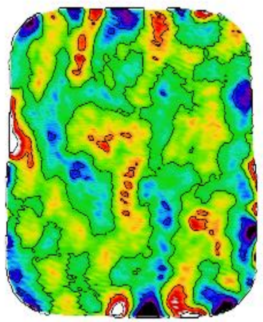
6^{th} testing campaign - Band 9 (950GHz) Single Dish Fast Mapping

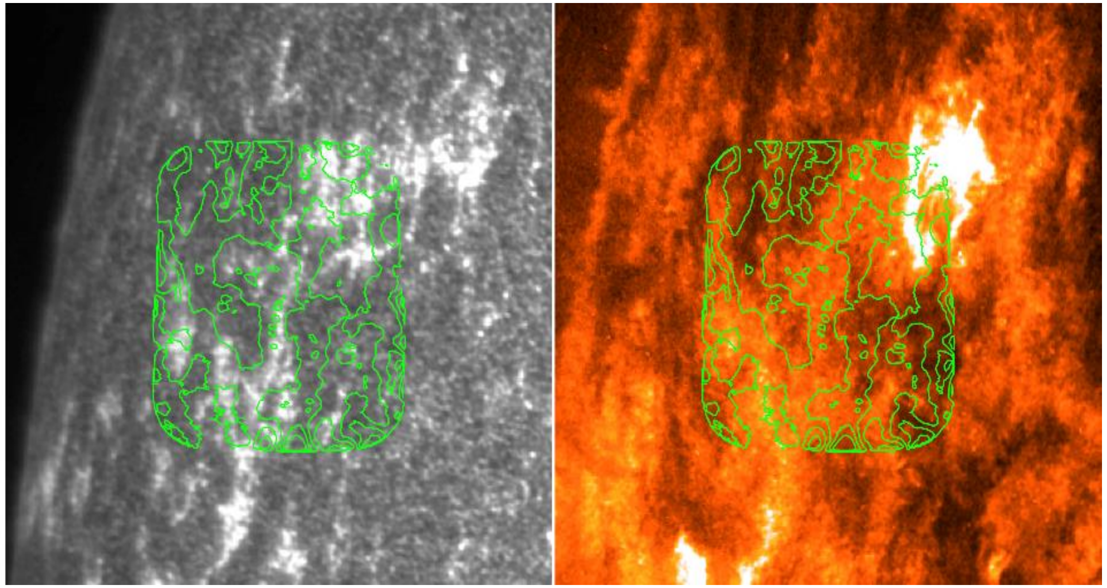




Quiet Sun Band6 1mm 0.8”@230 GHz

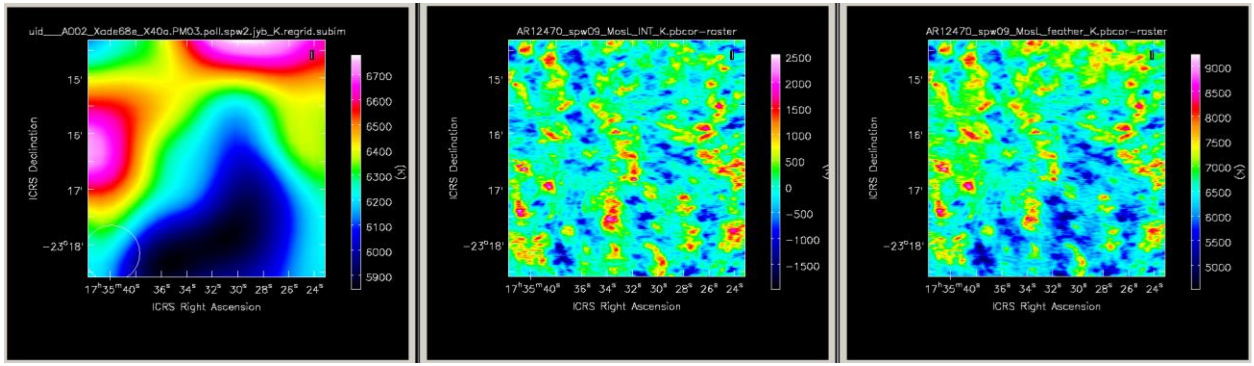
- Mosaic for small area (39 pts) with MD1 and MD2
- Mosaic-small: 39 pointings » 150”x150”@Band3 / **75”x75”@Band6**
- On 17 December 2015, we observed the QS near the limb with Band6/MD1
- The synthesize image from MD1 data (15:15 - 15:32UT) and UV cont. & He II image obtained with AIA/SDO

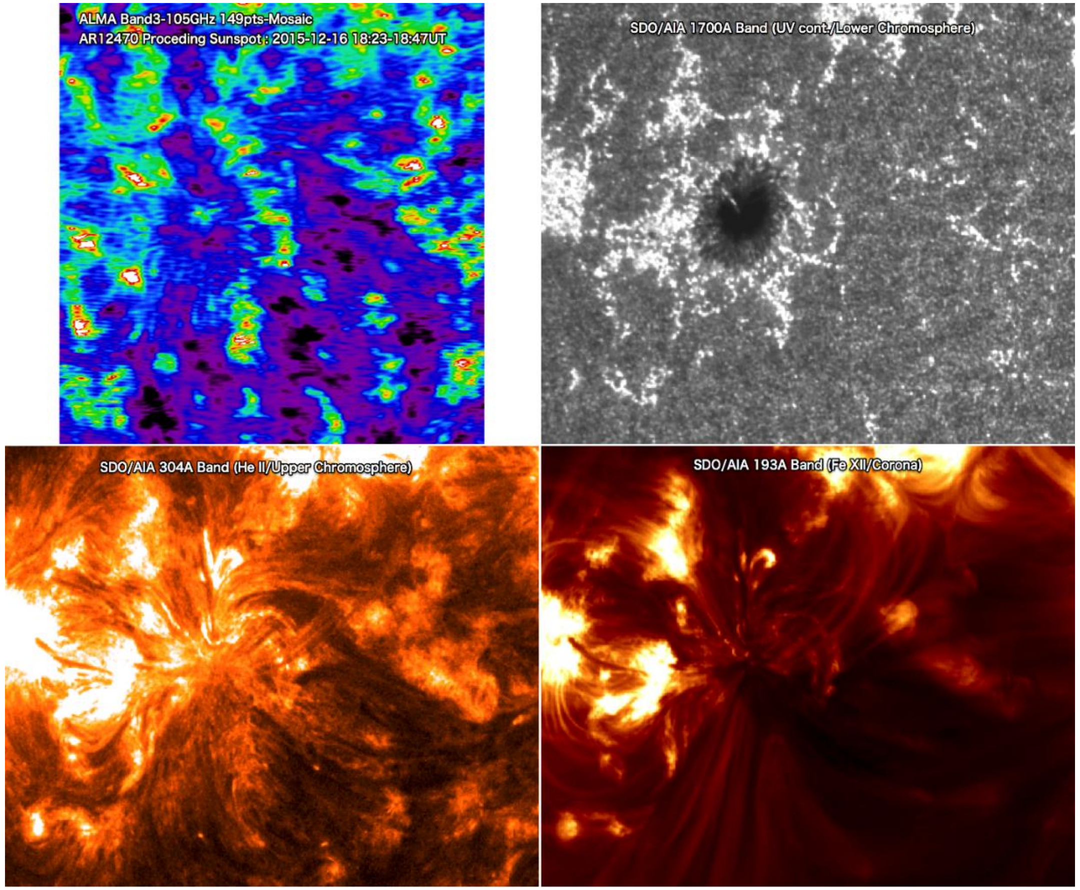




AR Band3 3mm C40-2 + ACA

- **AR Band3 3mm** C40-2 + ACA [Heterogeneous Array]
- Mosaic-Large: 149 pointings » **310”x310”@Band3 1.8”@100 GHz**
- Calibration, Imaging, and Feathering for the 149-pts MOSAIC observation with Band3
- The images show the effect of the feathering process. From left, **SD image, INT image (12m+7m) and Combined image.** It clearly reveals that SD image is essential for ALMA solar observation, not only for deriving the absolute brightness.

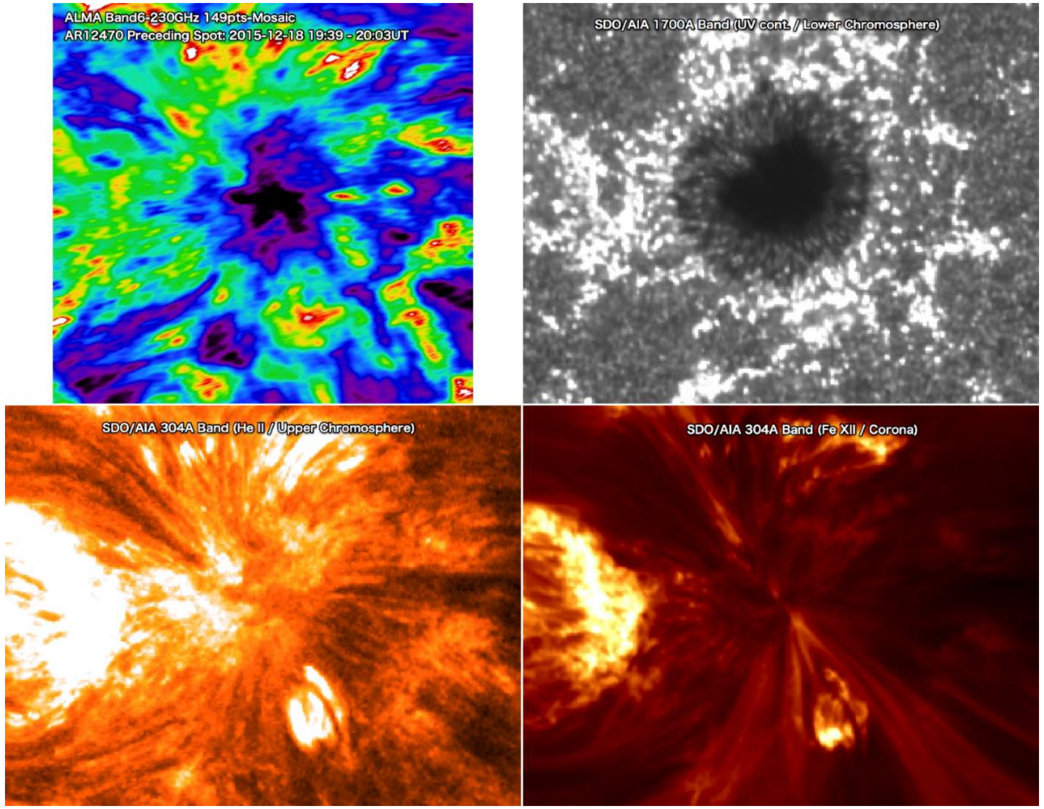


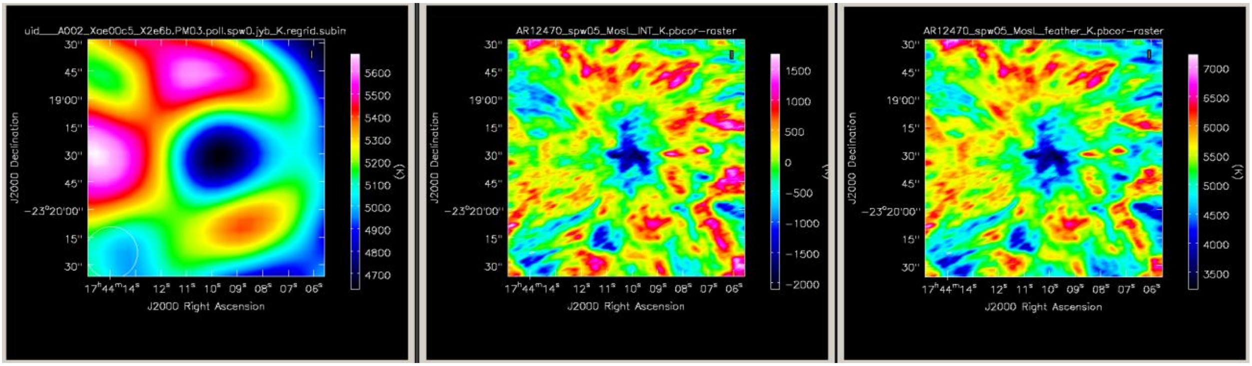


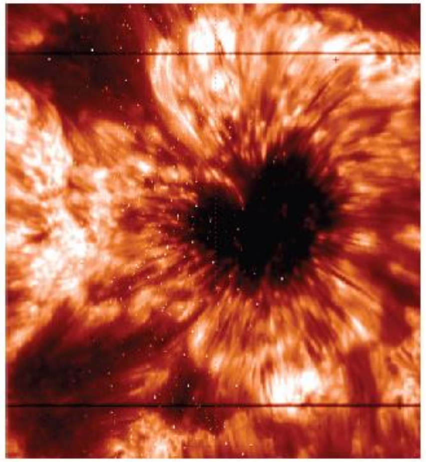
The co-alignment result between ALMA combined image and AIA/SDO images. QS (the right-lower part) is dark in ALMA image. Such gradient cannot be seen in the INT image, and it is effect of the feathering process.

AR Band6 1mm C40-2 + ACA

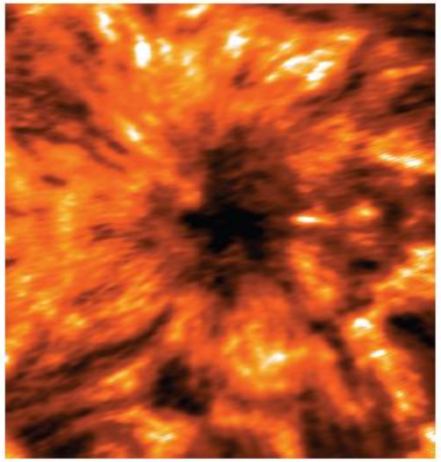
- Mosaic-Large: 149 pointings » 150”x150”@Band6
- **0.8”@230 GHz**
- The Feathering script and images for the 149-pts MOSAIC observation with Band6
- SD , INT and Combine images







IRIS Mg II k2v



ALMA 1.2 mm (149 pointings)

Results of testing campaigns

For cycle 4 Solar observing will be supported as a nonstandard observing mode in as follows:

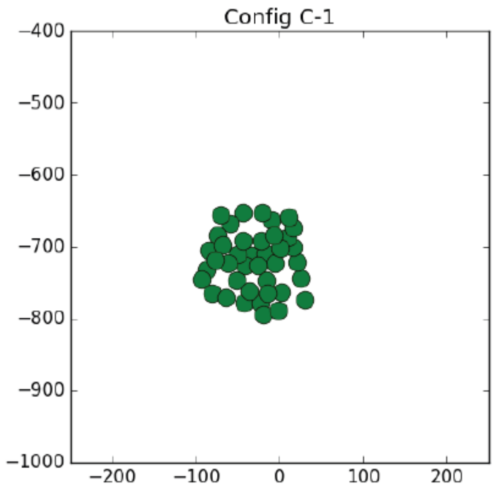
- Band 3 and band 6 continuum observations of the Sun will be supported
- Solar observing will only be offered for the most compact array configurations
- Both 7m and 12m antennas will be correlated by the baseline correlator
- Both single pointing and mosaicking (up to 150 pointings) interferometric observations of target sources will be supported
- Observations with the interferometer will be supported by fast-scanning total power (TP) maps of the full disk of the Sun

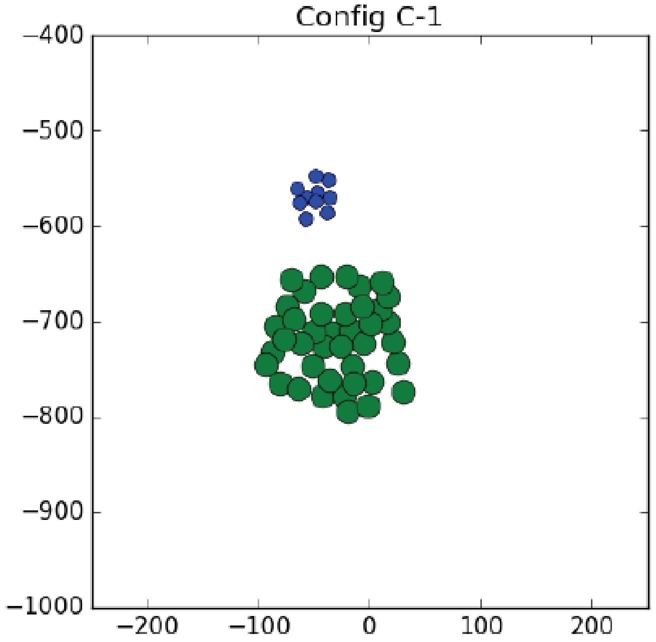
Supported Cy4 Configurations

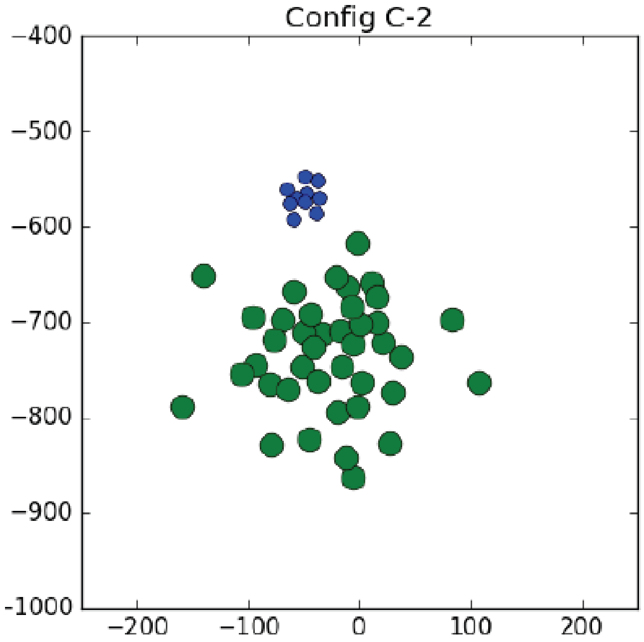
	Band	3	4	6	7	8	9	10
	Frequency (GHz)	100	150	230	345	460	650	870
Configuration								
7-m	θ_{res} (arcsec)	12.5	8.4	5.4	3.6	2.7	1.9	1.4
	θ_{MRS} (arcsec)	66.7	44.5	29.0	19.3	14.5	10.3	7.7
C40-1	θ_{res} (arcsec)	3.7	2.5	1.6	1.1	0.80	0.57	0.42
	θ_{MRS} (arcsec)	29.0	19.4	12.6	8.4	6.3	4.5	3.3
C40-2	θ_{res} (arcsec)	2.4	1.6	1.0	0.69	0.52	0.37	0.27
	θ_{MRS} (arcsec)	22.1	14.8	9.6	6.4	4.8	3.4	2.5
C40-3	θ_{res} (arcsec)	1.5	0.97	0.63	0.42	0.32	0.22	0.17
	θ_{MRS} (arcsec)	13.7	9.1	5.9	4.0	3.0	2.1	1.6
C40-4	θ_{res} (arcsec)	0.93	0.62	0.40	0.27	0.20	0.14	0.11
	θ_{MRS} (arcsec)	8.9	5.9	3.9	2.6	1.9	1.4	1.0
C40-5	θ_{res} (arcsec)	0.54	0.36	0.23	0.16	0.12	0.083	0.062
	θ_{MRS} (arcsec)	6.0	4.0	2.6	1.7	1.3	0.93	0.69
C40-6	θ_{res} (arcsec)	0.35	0.23	0.15	0.10	0.076	0.054	0.040
	θ_{MRS} (arcsec)	3.1	2.1	1.3	0.90	0.67	0.48	0.36
C40-7	θ_{res} (arcsec)	0.21	0.14	0.090	0.060	0.045	0.032	0.024
	θ_{MRS} (arcsec)	1.8	1.2	0.77	0.52	0.39	0.27	0.20
C40-8	θ_{res} (arcsec)	0.12	0.079	0.052	0.034	-	-	-
	θ_{MRS} (arcsec)	1.3	0.87	0.57	0.38	-	-	-
C40-9	θ_{res} (arcsec)	0.066	0.044	0.029	-	-	-	-
	θ_{MRS} (arcsec)	0.78	0.52	0.34	-	-	-	-

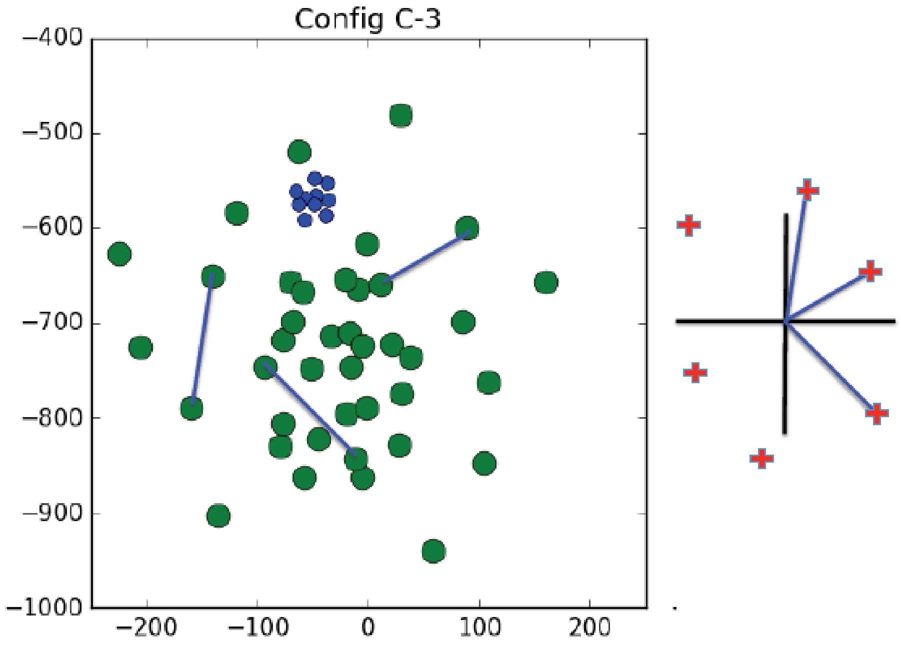
(1) Planned Start Date	(2) Configuration (planned campaigns)	(3) Longest baseline	(4) LST with best observing conditions	(5) LST with unstable observing conditions	(6) PI Observing Time (days)
14 October 2016	C40-7	3.7 km	~22h - 11h	~11h-22h	13
4 November 2016	C40-6	1.8 km	~23h - 12h	~12h-23h	11
25 November 2016	C40-5	1.1 km	~1h - 13h	~13h-1h	7
9 December 2016	C40-4	0.70 km	~2h - 14h	~14h-2h	7
23 December 2016	C40-3 (Solar)	0.46 km	~3h - 15h	~15h-3h	11
19 January 2017	C40-2 (Solar)	0.27 km	~4h - 17h	~17h-4h	9
1 February 2017	*February maintenance period*				
16 March 2017	C40-1 (Solar/VLBI)	0.15 km	~8h - 22h	22h-8h	17
6 April 2017	C40-3 (Solar/VLBI)	0.46 km	~9h - 23h	~23h-9h	11
27 April 2017	C40-5	1.1 km	~10h - 1h	~1h-10h	7
11 May 2017	*Move to configuration C40-9*				
8 June 2017	C40-9	12.6 km	~12h - 3h	~3h-12h	16
6 July 2017	C40-8	6.8 km	~14h - 5h	~5h-14h	22
17 August 2017	C40-7	3.7 km	~17h - 8h	~8h-17h	23

Supported Cy4 Configurations









Solar ALMA future

First opportunity to apply for ALMA observations: NOW

Solar Observations in Cycle 4 (October 2016-September 2017)

Capabilities:

Interferometry + Total Power

Band 3 84-116GHz, 3.6-2.6mm

Band 6 6211-275GHz, 1.4-1.1mm

Compact configurations: baselines up to ~500m

C40.3 → 1.2”@Band3, 0.5”@Band6

C40.2 → 1.8”@Band3, 0.8”@Band6

FOV for **single pointing**:

~58”@Band 3, ~25”@Band 6

For bigger FOV (2’-5’) MOSAIC obs :

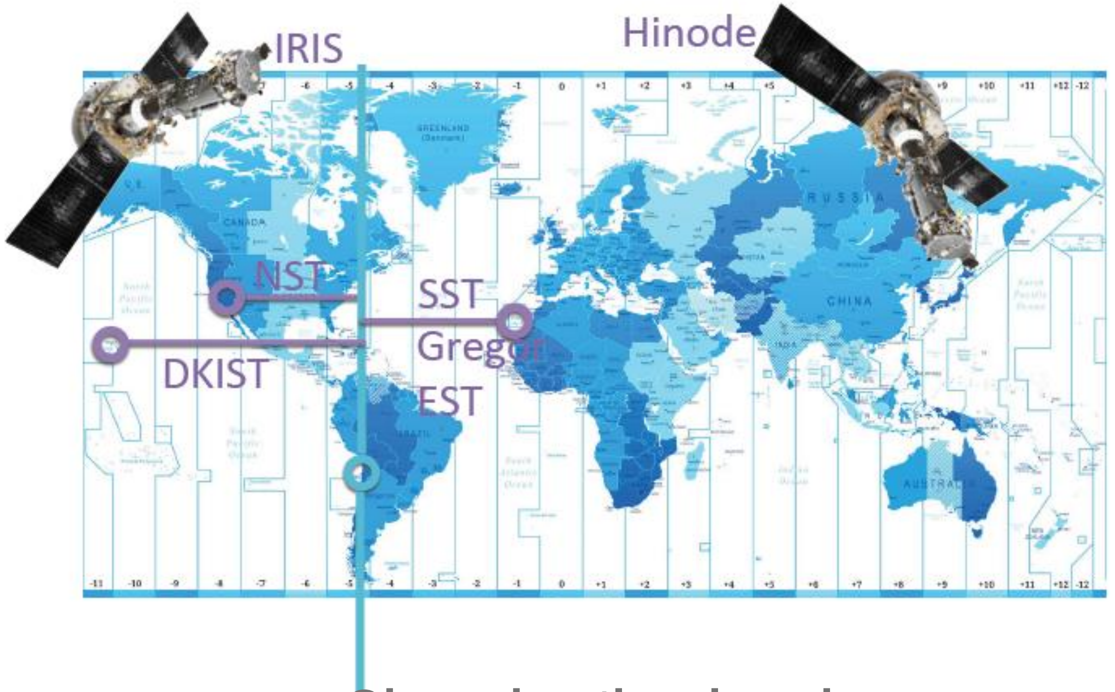
up to 150 pts (300 x 300 arcsec/per ~40 mins)

Time Cadence 2 sec

Polarization: Only Stokes-I (XX & YY)

possible **co-observing with other observatories (IRIS, Hinode, NST, SDO, etc.)**

Coordinated Observations



Observing time in a day

- Summer [Max] : 10:00 ~ 17:00 CLT
- Spring/Autumn Equinox: 10:30 ~ 16:30 CLT
- Winter [Min] : 12:30 ~ 14:30 CLT

Solar ALMA future

First opportunity to apply for ALMA observations: NOW

Solar Observations in Cycle 4 (October 2016-September 2017)

Limitations:

Flux density of calibrators

- Bandpass calibrator: > 5 Jy @ Observing Frequency.
- Phase / Flux calibrator: > 1.5 Jy @ Observing Frequency.
- Mars can be used for a flux calibrator.
- **Observing time in a day**

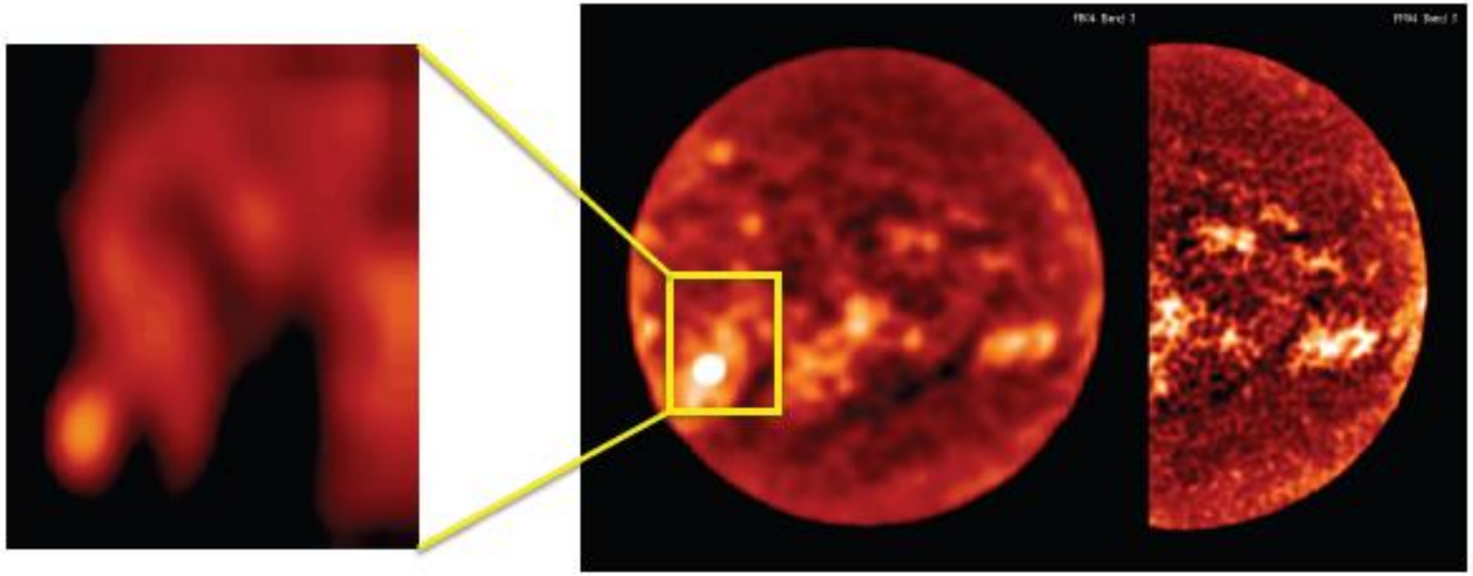
7m antennas are essential for solar observations • Because 7m-antennas are located very closely "Shadowing" happens easily when the elevation of the target is lower than 40 degrees.

- Summer [Max] : 10:00 ~ 17:00 CLT
- Spring/Autumn Equinox: 10:30 ~ 16:30 CLT
- Winter [Min] : 12:30 ~ 14:30 CLT
- **Output Data**: Cross/Auto-correlations & data of the BB detectors.
- **Amp calibration between scientific scans**
- In addition, the measurements of Tsys of the target region (Sun) and Toff have to be added for the Amp calibration between scientific scans

maximum length of uninterrupted scans ~10min

Cycle 5 Solar Capabilities

- Bands 7 and 9 (350 and 650 GHz; 850 and 450 microns)
- Spectral line capability (bands 3, 6, 7, & 9)
- Polarimetry
- Support of subarrays
- Integration times <2 s (Cy4)
- Fast TP mapping of sub-regions



Call for Proposals

https://almascience.nrao.edu/proposing/call-for-proposals

ALMA Cycle 4 proposal submission is open at:
15:00 UT on Tuesday 22 March 2016.

The ALMA Cycle 4 proposal submission deadline is:
15:00 UT on Thursday 21 April 2016.

Call for Proposals
Cycle 4 News
Proposing Guidance
Proposer's Guide
Cycle 4 Capabilities
Observing Tool
Sensitivity Calculator
Proposal Template
Duplications
ALMA Primer
Technical Handbook