National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Approaching the finish line with GeoSTAR

Bjorn Lambrigtsen

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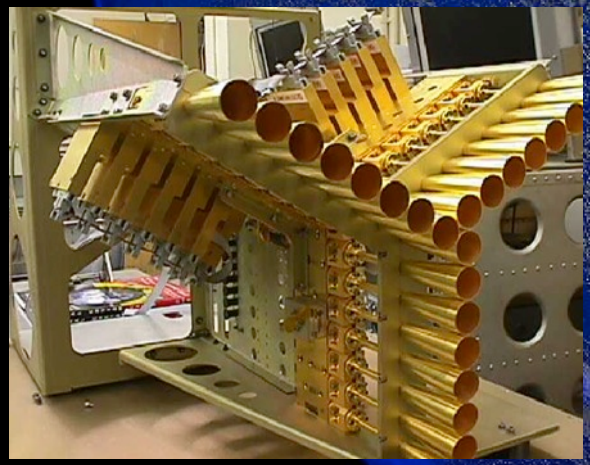

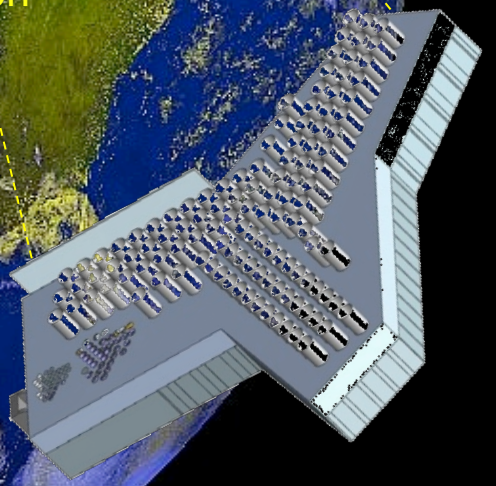

Earth Science Technology Forum
Leesburg; October 27-29, 2014

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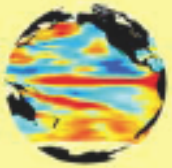
GeoSTAR Development History

Decadal survey: PATH mission

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$460 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M

Precipitation and



Sea surfac
temperatu

Temperatu
humidity pr

Constraints on
models for boundary
layer, cloud, and
precipitation
processes

PATH applications

Weather forecasting	All-weather soundings, in cloudy and stormy scenes Soundings @<50/25 km every 15-30 minutes (continuous) Synoptic rapid-update soundings Forecast error detection; 4DVAR applications
Hurricane & severe-storm diagnostics	Location, intensity & vertical structure of deep convection NRT atmospheric instability; tornado precursor detection Intensification/weakening in NRT, frequently sampled Measure all H_2O phases: vapor, liquid, ice, rain/snow Operational analysis, forecast verification Improved model microphysics
Rain	Full hemisphere @ ≤ 25 km every 15 minutes Directly measure storm and diurnal total rainfall: predict flooding events Snowfall, light rain, intense convective precipitation
Tropospheric wind profiling	1000-300 mb; very high temp.res.; in & below clouds Air quality applications (pollution transport)
Climate research	Stable & continuous MW observations Long term trends in T & q and storm statistics Fully resolved diurnal cycle ENSO; monsoon; tropical moisture flow into the US "Science continuity": GeoSTAR ≈ AMSU

geographic
distribution and
magnitude of storm
surge and rain
accumulation

PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer **= GeoSTAR**	$450 M

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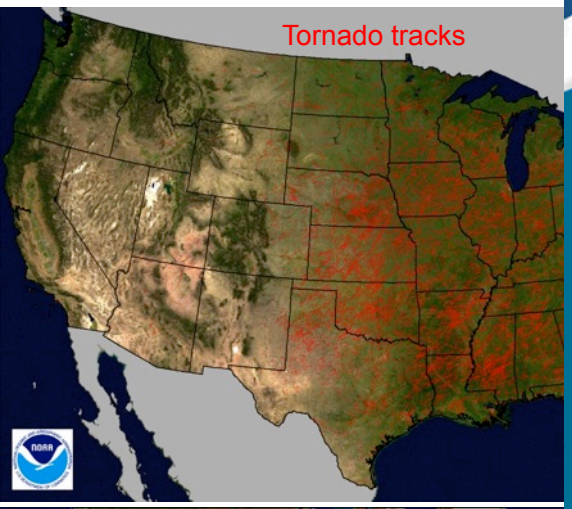
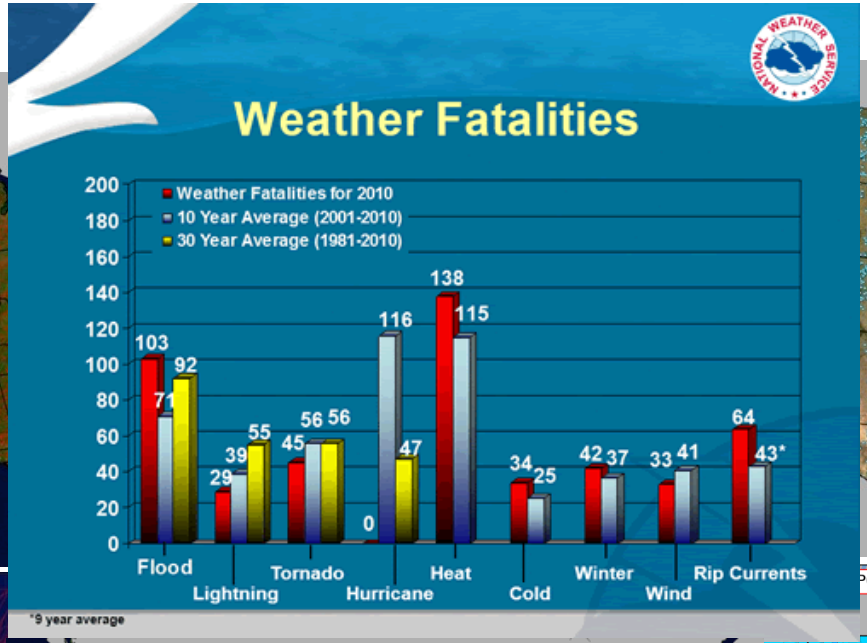
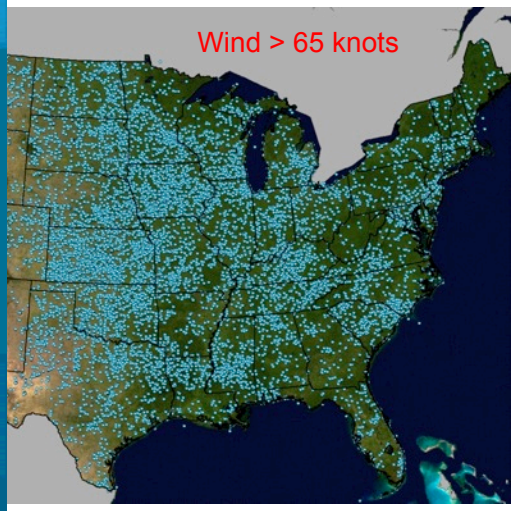
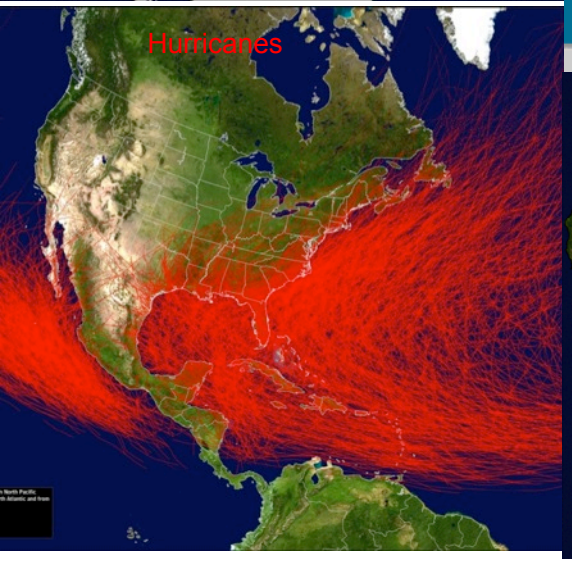
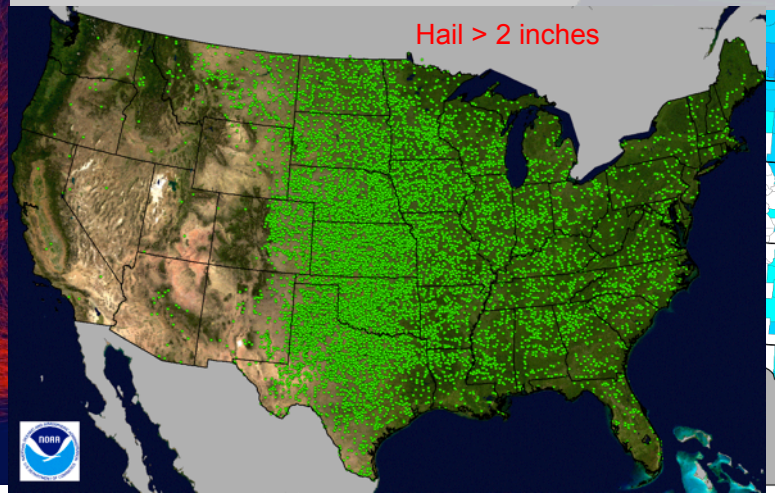
Severe storms may be getting worse

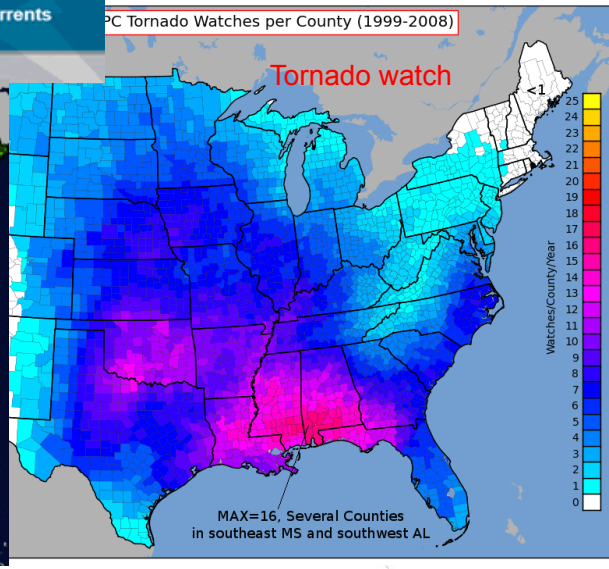












GeoSTAR timeline

- Concept development
  - NMP/EO-3 proposal (1998-1999)
  - NRC white paper (2005)
  - NRC Decadal Survey (2007)
- ESTO technology development
  1. IIP-03 (2003-2006): Proof-of-concept prototype
  2. ACT-05 (2006-2008): MIMRAM receivers
  3. IIP-07 (2008-2011): Key technology
  4. IIP-10 (2011-2015): Risk reduction
- Space implementation
  - *Venture mission (before 2020?)*
  - *PATH mission (~202X?)*

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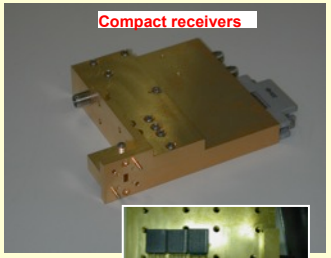
GeoSTAR Development – IIP-03

Proof of concept

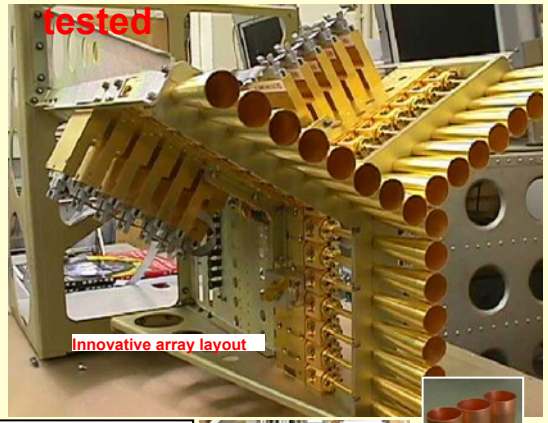
1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
NMP/EO-3: GEO/SAMS				IIP-03: GeoSTAR ptototype									
					Study								

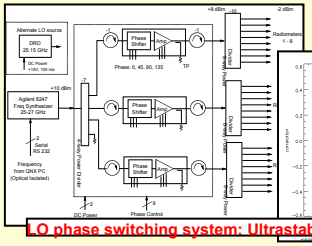
STAR sounder concept

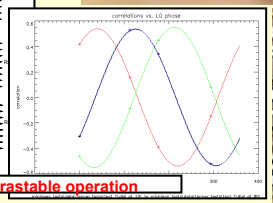
STAR concept and key technologies developed & tested


Compact receivers


Low-power MMICs

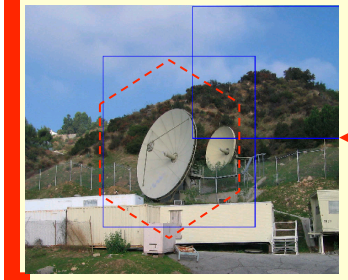

Innovative array layout

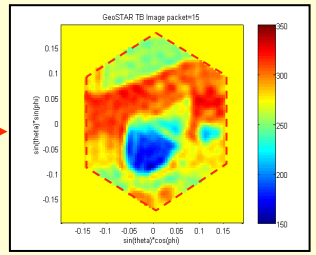

LO phase switching system: Ultrastable operation




Correlator:
- Efficient
- Redundant
- OK for ASICs


Feedhorns: Low mutual coupling





First images at 50 GHz by aperture synthesis

Partnership with NOAA: Mission study

Spatial resolution	Frequency band	50 GHz	89 GHz	118 GHz	183 GHz
	Antenna element spacing	2.1 cm	1.2 cm	0.9 cm	0.6 cm
150 km	Number of elements	← 3x32 →			
	Arm length	0.7 m	0.4 m	0.3 m	0.2 m
	Power	75 W	75 W	75 W	75 W
	Mass	75 kg	50 kg	45 kg	40 kg
100 km	Number of elements	← 3x48 →			
	Arm length	1.0 m	0.6 m	0.45 m	0.3 m
	Power	115 W	115 W	115 W	115 W
	Mass	100 kg	70 kg	60 kg	50 kg
75 km	Number of elements	← 3x64 →			
	Arm length	1.3 m	0.8 m	0.6 m	0.4 m
	Power	150 W	150 W	150 W	150 W
	Mass	125 kg	90 kg	80 kg	70 kg
50 km	Number of elements	← 3x96 →			
	Arm length	2.0 m	1.1 m	0.85 m	0.6 m
	Power	235 W	235 W	235 W	235 W
	Mass	200 kg	130 kg	115 kg	100 kg
30 km	Number of elements	← 3x160 →			
	Arm length	3.4 m	1.9 m	1.4 m	0.9 m
	Power	400 W	400 W	400 W	400 W
	Mass	300 kg	225 kg	190 kg	150 kg

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GeoSTAR Development – JPL R&TD

Calibration & performance assessment

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012

NMP/EO-3: GEO/SAMS

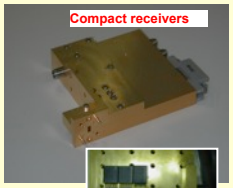
IIP-03: GeoSTAR ptototype

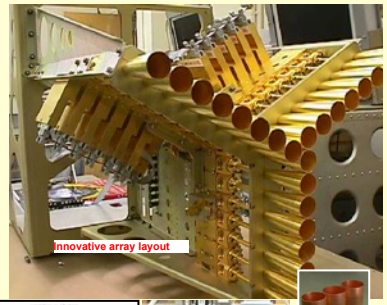
Study

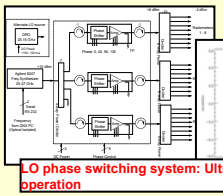
JPL R&TD: GeoSTAR calibration

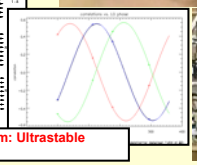
STAR sounder concept

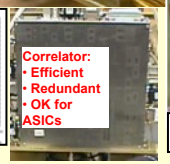
STAR concept and key technologies developed & tested



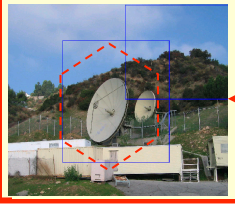


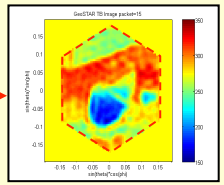






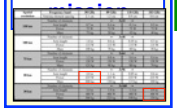
LO phase switching system: Ultrastable operation

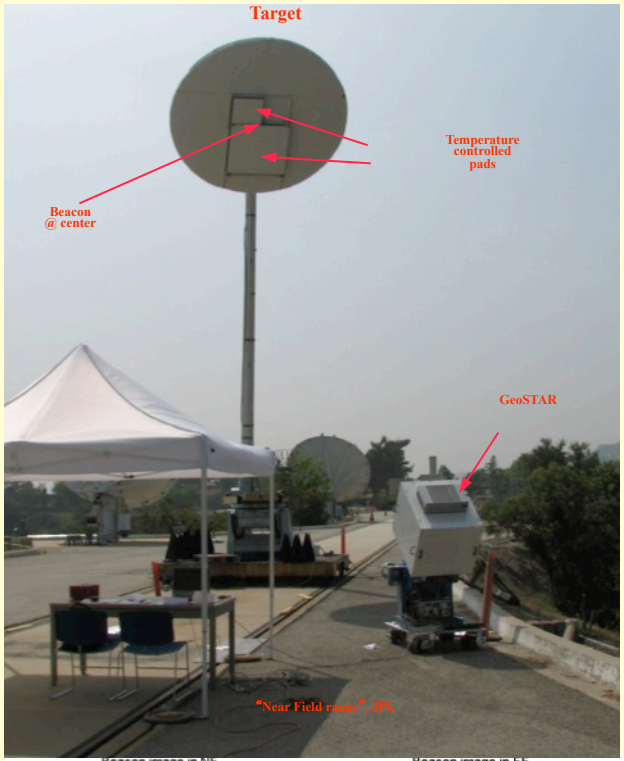


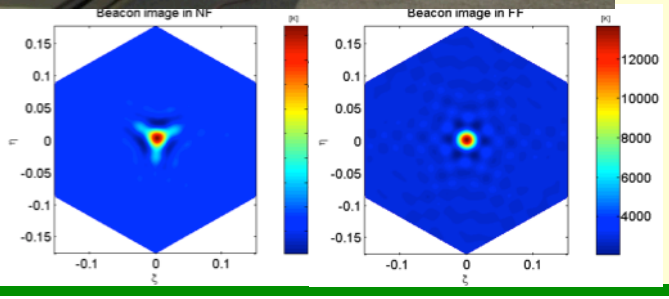


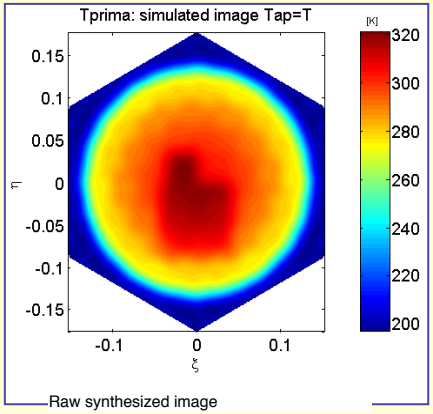
First images at 50 GHz by aperture synthesis

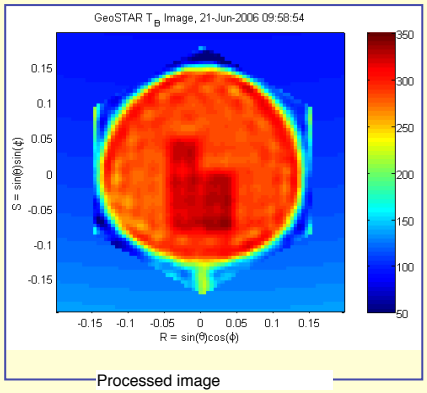
NOAA











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GeoSTAR Development – ACT-05

183-GHz technology

1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012

NMP/EO-3: GEO/SAMS

STAR sounder concept

IIP-03: GeoSTAR ptototype

Study

Study

ACT: 183-GHz MMIC development

IPP: MMIC development

JPL R&TD: GeoS

STAR concept and key technologies developed & tested

Compact receivers

Low-power MMICs

Innovative array layout

Correlator:
- Efficient
- Redundant
- OK for ASICs

LO phase switching system: Ultrastable operation

Feedhorns: Low mutual coupling

First images at 50 GHz by aperture synthesis

Design innovations

Calibration, perform-ance verification

Target

Beacon @ center

Temperature controlled pads

GeoSTAR

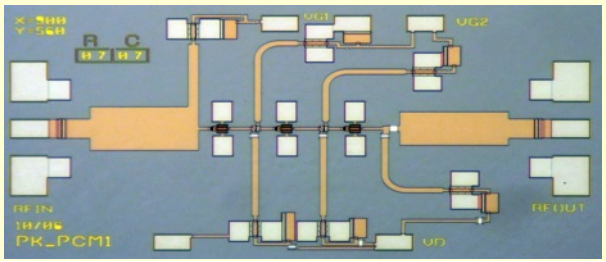
Raw synthesized image

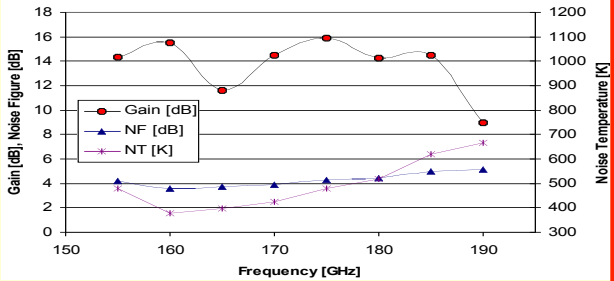
Processed image

NOAA

Breakthrough MMIC performance

AEROWAVE INC.





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GeoSTAR Development – IIP-07

Technology development

1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012

NMP/EO-3: GEO/SAMS

STAR sounder concept

IIP-03: GeoSTAR ptototype

Study

Study

Study

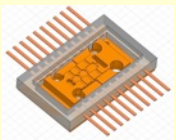
ACT: 183-GHz MMIC development

IPP: MMIC development

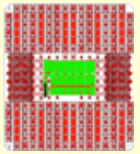
JPL R&TD: GeoSTAR calibration

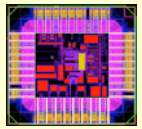
IIP-07: GeoSTAR/PATH risk reduction

Receivers



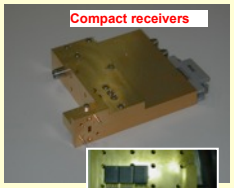
ASICs



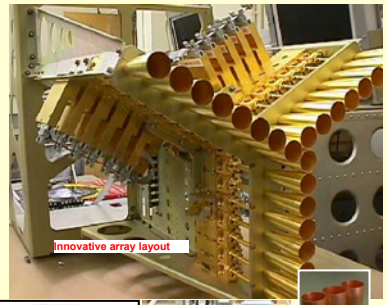


STAR concept and key technologies developed & tested

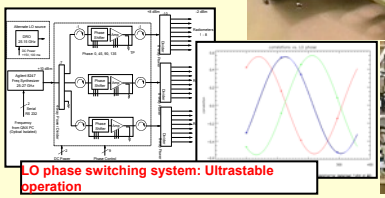
Compact receivers



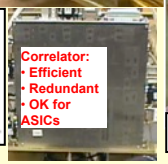
Low-power MMICs



Innovative array layout



LO phase switching system: Ultrastable operation



Correlator:
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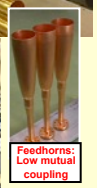
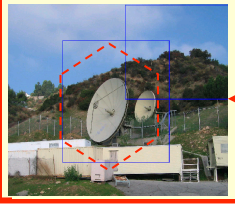
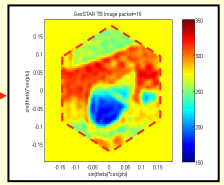


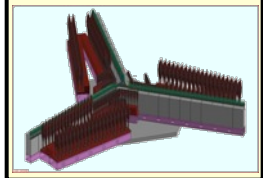
Feedhorns: Low mutual coupling



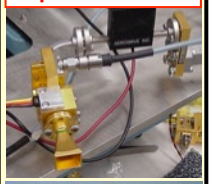


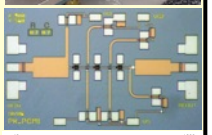
First images at 50 GHz by aperture synthesis

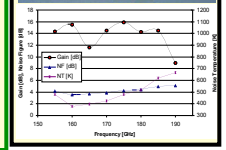
Design innovations



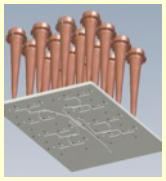
Breakthrough MMIC performance





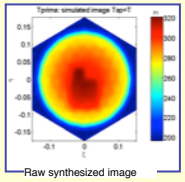


Antenna design

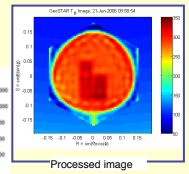


Target

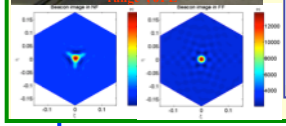
Calibration, perform-ance verification



Raw synthesized image

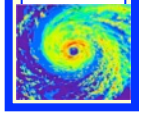


Processed image

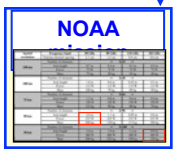


IIP-07: NOAA co-funding

Application studies



NOAA



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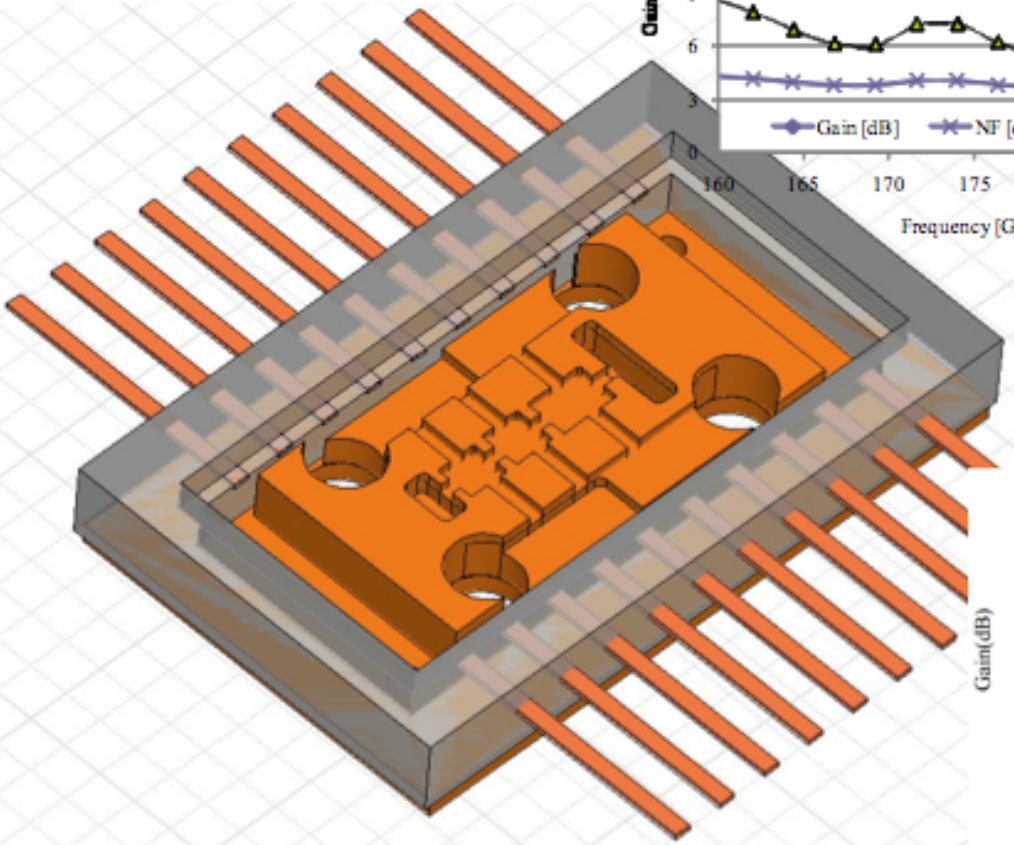
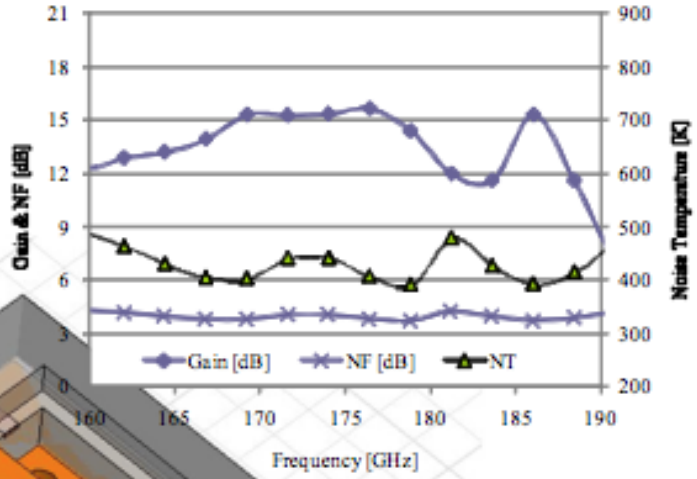
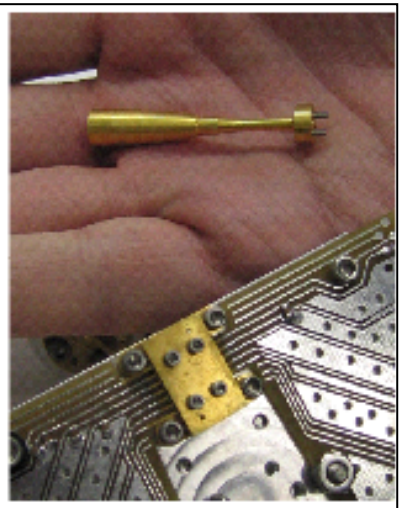
GeoSTAR Development – IIP-07

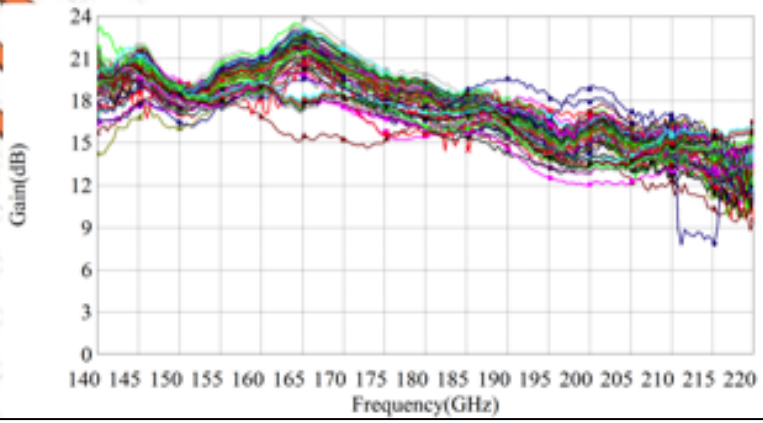
183-GHz receiver (fab 50 samples)

- Conversion gain 10 dB
- Power consumption <60mW
- Mass <3g
- Physical size .375"x.3"x.2"









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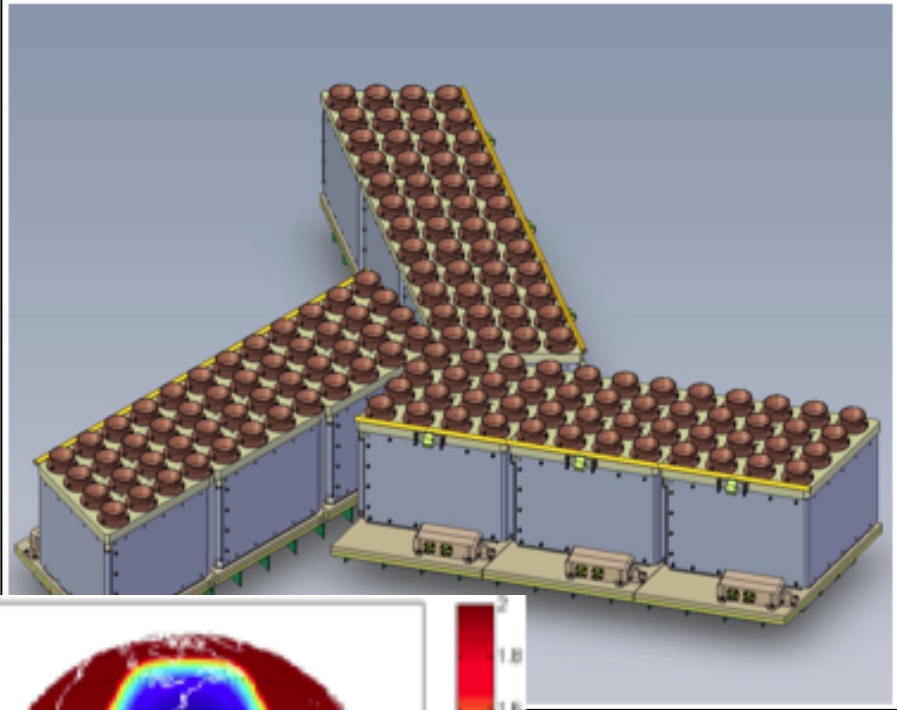
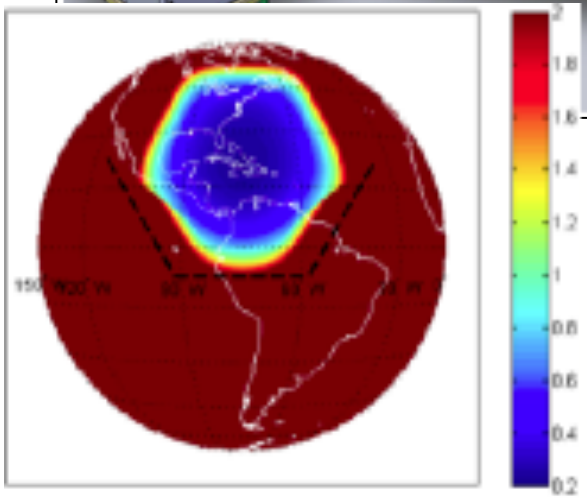
GeoSTAR Development – IIP-07

New antenna design (demo)



- Develop 50 low-noise 183-GHz receivers
- Develop 3 2x8-element receiver sub-array modules
- Develop low-power Application-Specific Integrated Circuit (ASIC) correlator chips
- Develop low-mass/power signal distribution system
- Develop functional 183-GHz 2D STAR prototype



⇐ Sharply bounded FOR
Large alias-free region
NEDT < 1/3 K

Frequency(GHz)

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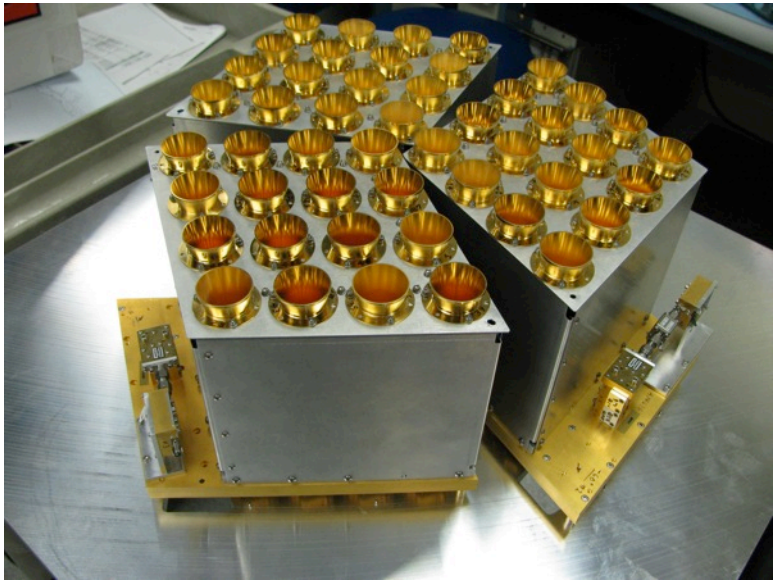
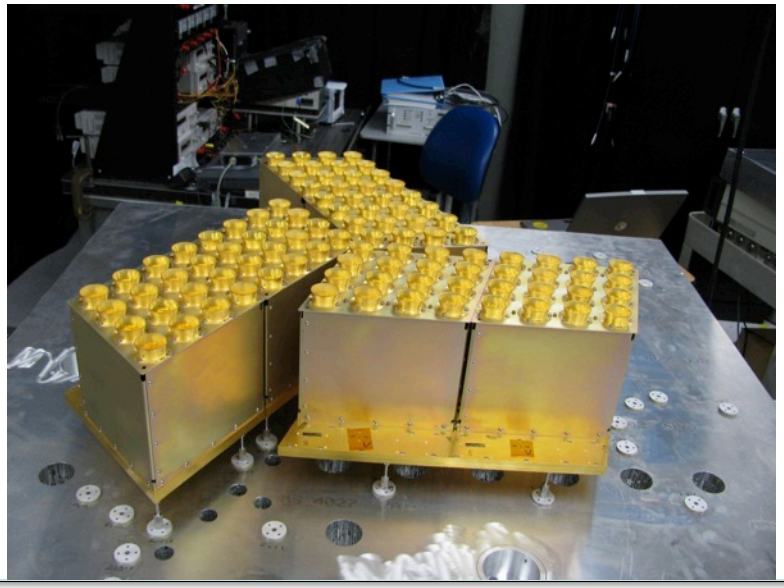
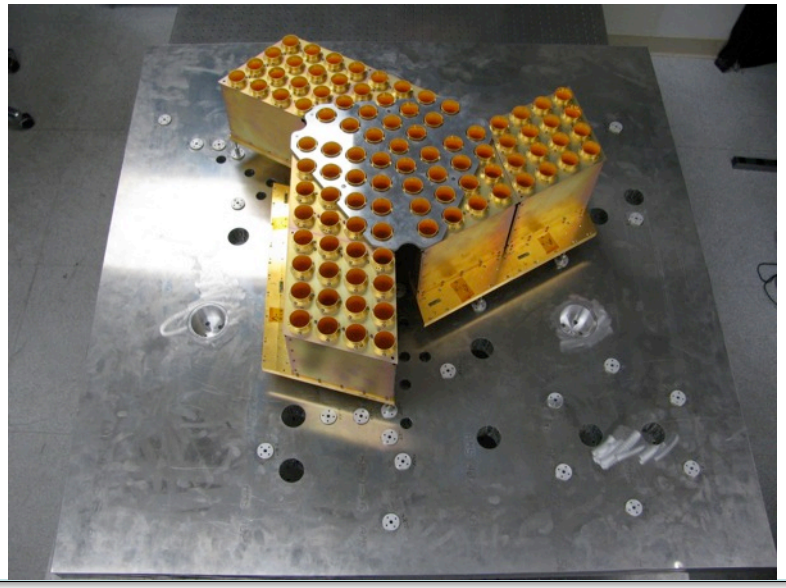
GeoSTAR Development – IIP-07

Antenna subarray assemblies







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GeoSTAR IIP-10: Correlator, Part 1

Small 5x5 design demo chip

1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012

NMP/EO-3: GEO/SAMS

STAR sounder concept

STAR concept and key technologies developed & tested

Compact receivers

Low-power MMICs

Innovative array layout

Correlator:
- Efficient
- Redundant
- OK for ASICs

LO phase switching system: Ultrastable operation

Feedhorns: Low mutual coupling

First images at 50 GHz by aperture synthesis

IIP-03: GeoSTAR ptototype

Study

Study

Study

ACT: 183-GHz MMIC development

IPP: MMIC development

JPL R&TD: GeoSTAR calibration

Design innovations

Calibration, perform-ance verification

Target

Beacon @ center

Temperature controlled pads

GeoSTAR

"Near-field range"

Raw synthesized image

Processed image

NOAA

Receivers

Breakthrough MMIC performance

IIP-07: GeoSTAR/PATH risk reduction

ASICs

Antenna design

IIP-10: PATH risk reduct

IIP-07: NOAA co-funding

Application studies

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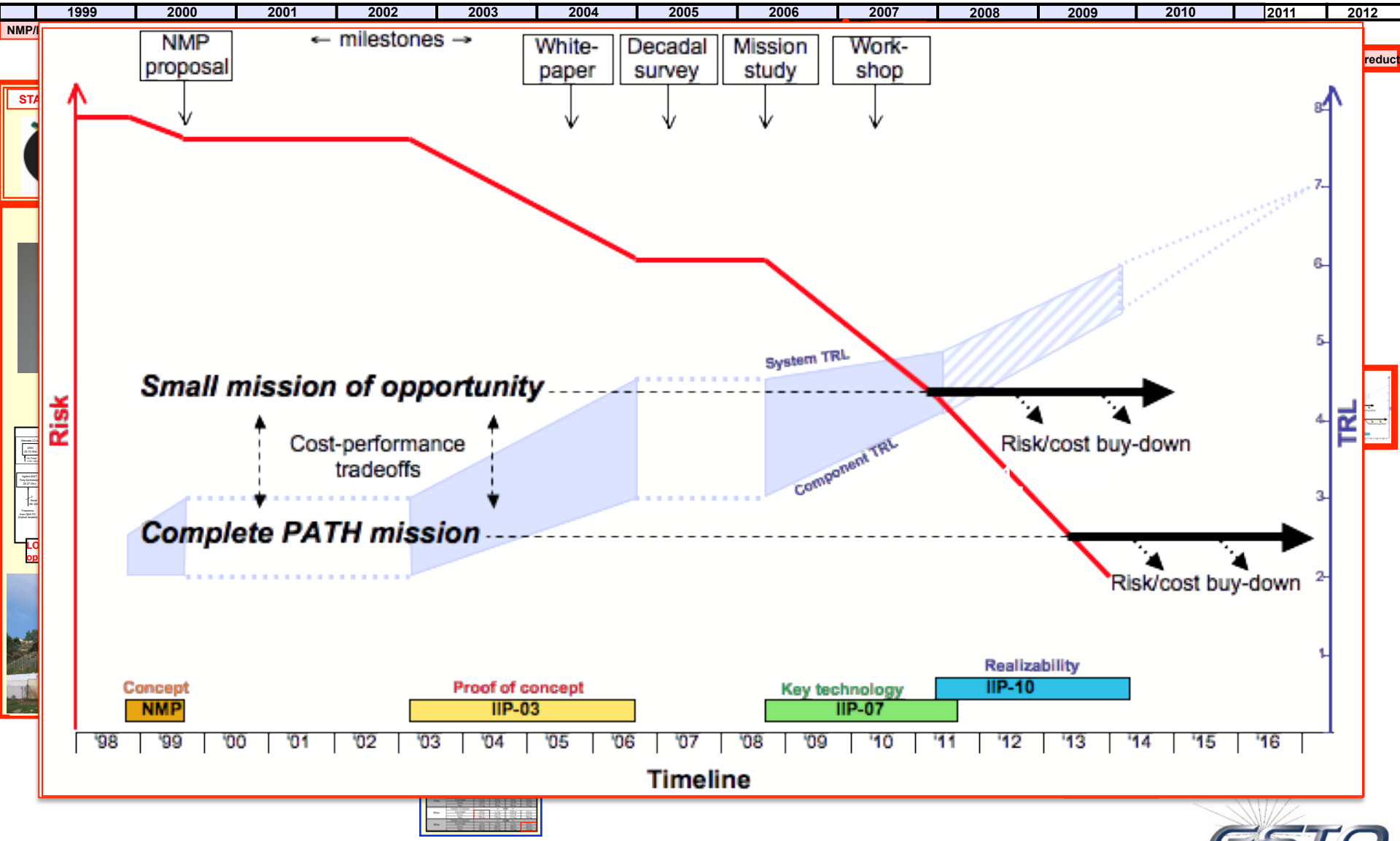
GeoSTAR IIP-10: Correlator, Part 1

Small 5x5 design demo chip



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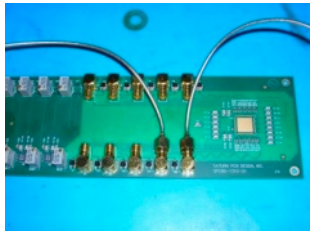
GeoSTAR IIP-10: Correlator, Part 1

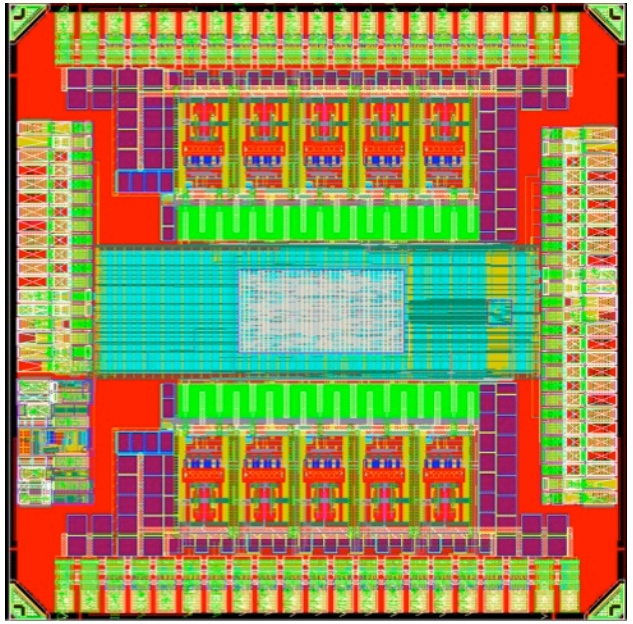
Small 5x5 design demo chip

Correlator ASIC development

A 5x5 digitizer/correlator and evaluation board was built to provide risk reduction for the development of the larger A/D correlator ASIC.

- Test A/D and correlator cells together to uncover design or implementation flaws
- Determine crosstalk between channels





Initial tests indicated problems, but design was fixed, chip re-spun and tested

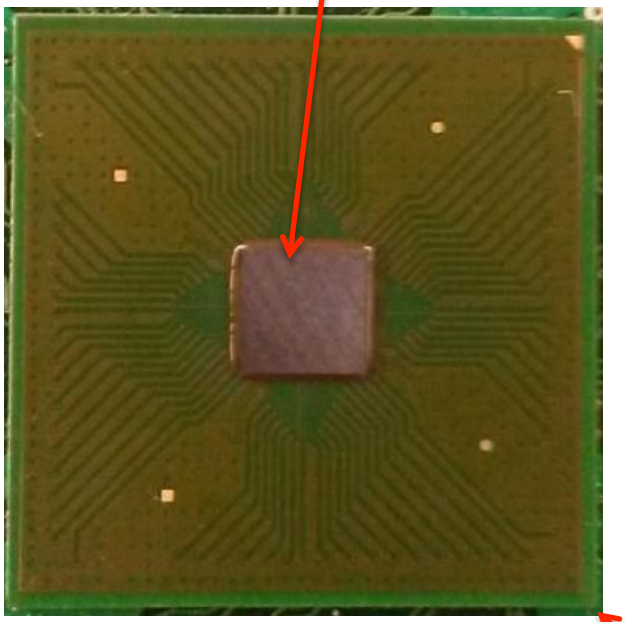
Tested for rad-hardness: OK

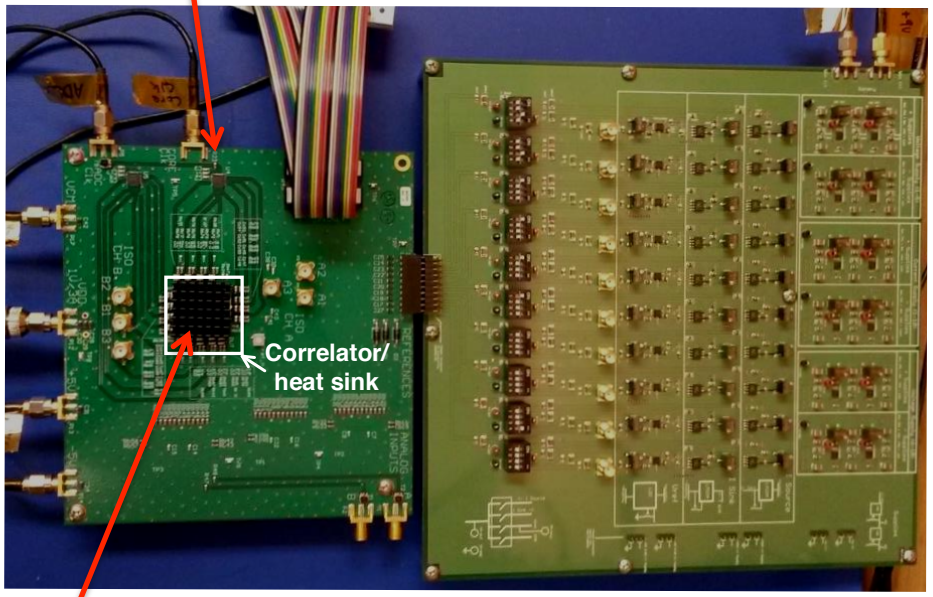
GeoSTAR IIP-10: Correlator, Part 2

Chip and test board

Chip (2.4 mm square)

Test board, with chip heat sink

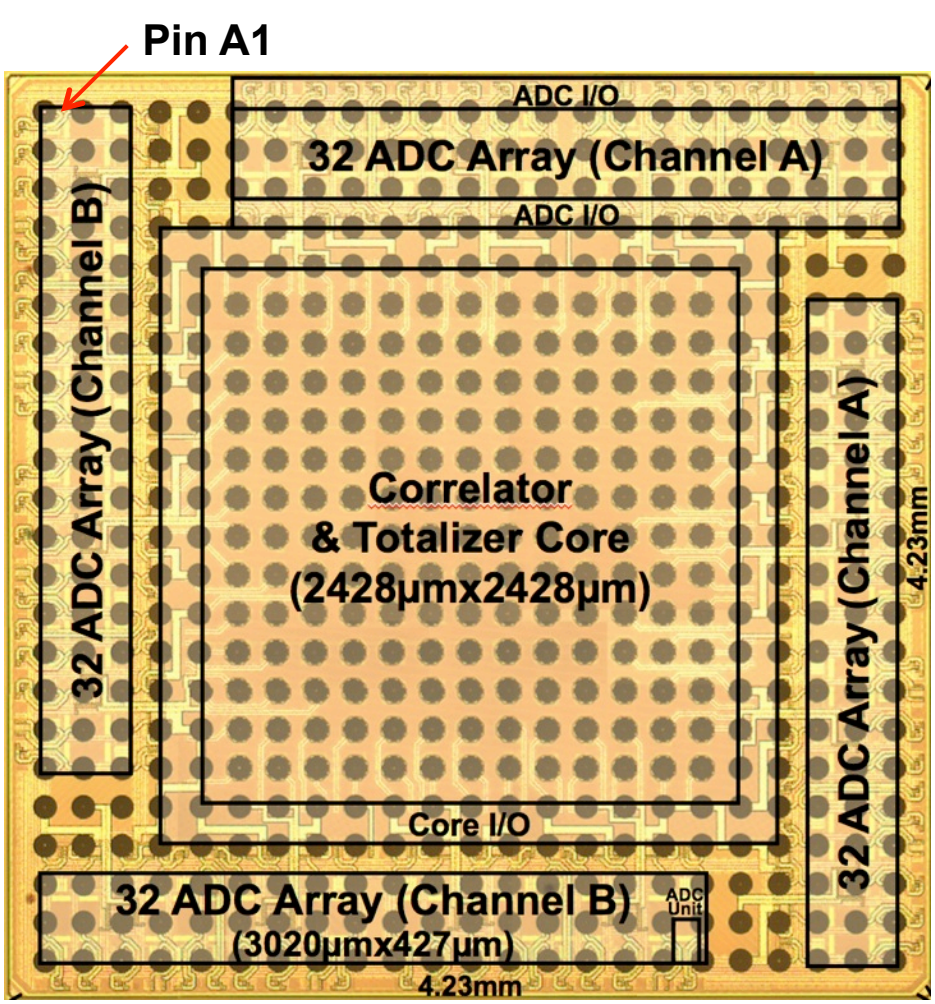




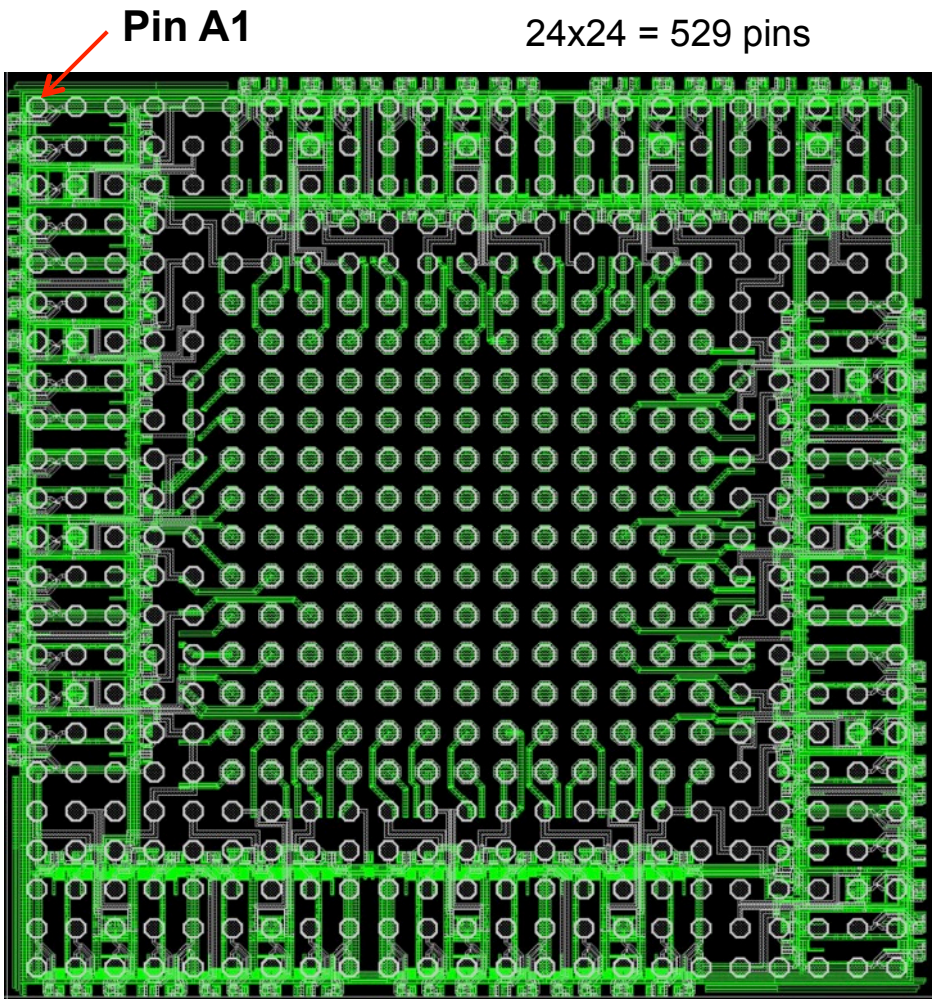
Substrate carrier (3/4” square)

GeoSTAR IIP-10: Correlator, Part 2

Chip orientation



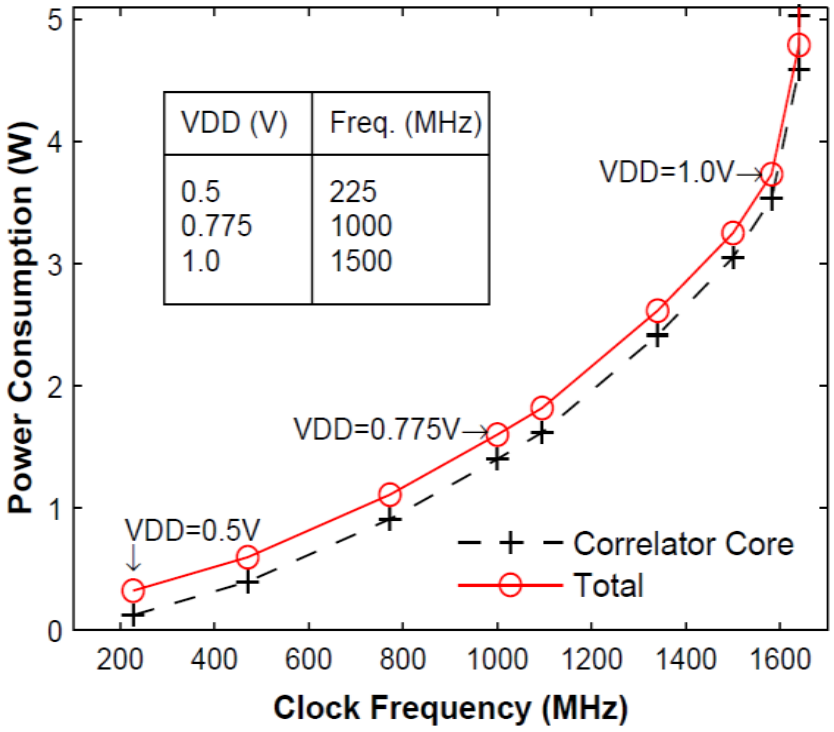
- Die Photo -



- Layout (M9, AP) -

GeoSTAR IIP-10: Correlator, Part 3

Specs & power consumption



	This work
# of Channels	128
# of Correlators	4096
Channel Bitwidth	2
On-Chip ADCs	yes, 128
Logic Family	static
Correlation Efficiency (%)	>90% @ >30dBm
Isolation (dB)	-42.4
Technology	65nm
Total Power (W)	1.44 @775mV, 1GHz 3.73@1V, 1.5GHz
Energy per Correlation (pJ/correlation/cycle)	0.35 @775mV, 1GHz 0.61 @1V, 1.5GHz (2b corr + ADC)
Core Area (mm^2) Chip Area (mm^2)	5.9 17.9
Max Performance (T correlation/s)	6.14 @1V, 1.5GHz

[a]: a 1-bit correlation is just XOR

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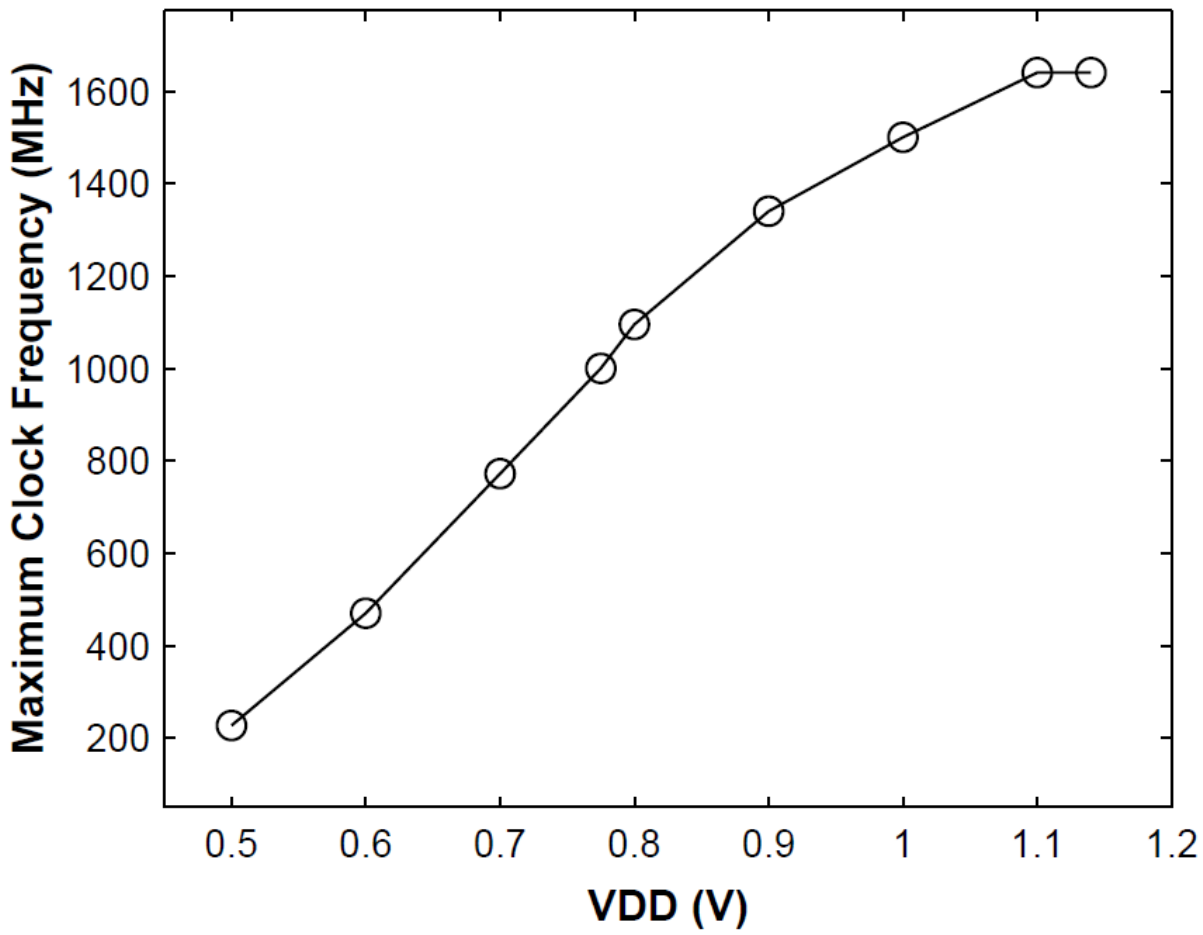
GeoSTAR IIP-10: Correlator, Part 3

Max clock rate 1.6 GHz (1 GHz required)



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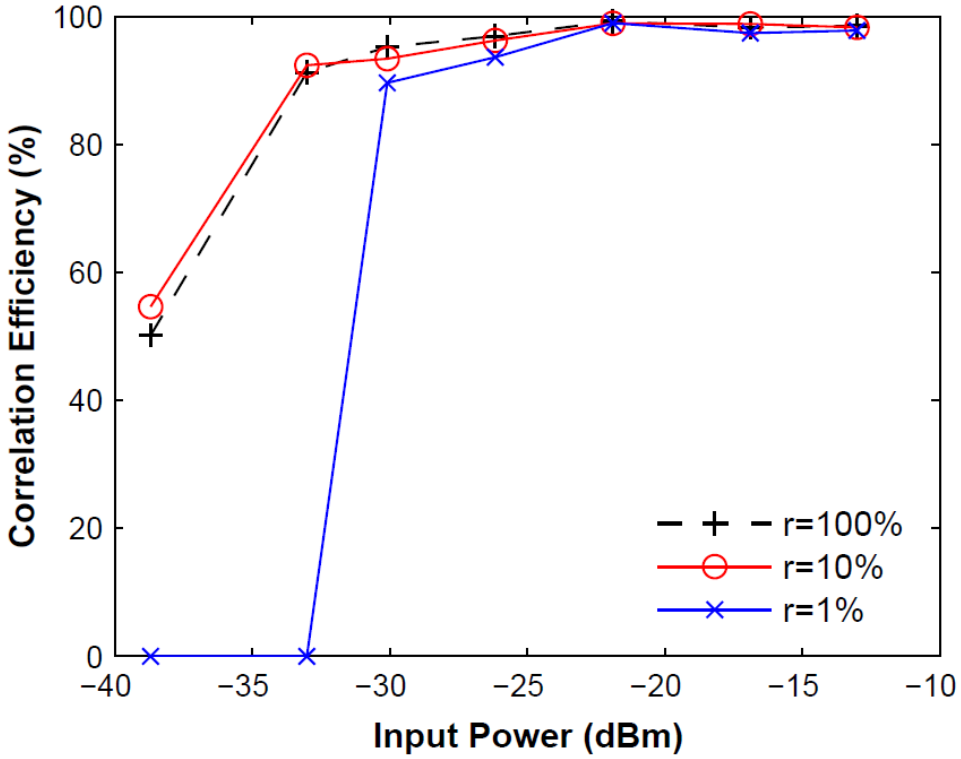
GeoSTAR IIP-10: Correlator, Part 3

Excellent correlation efficiency



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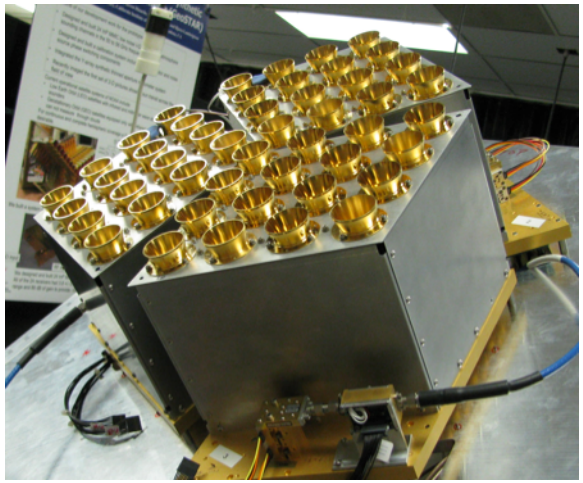
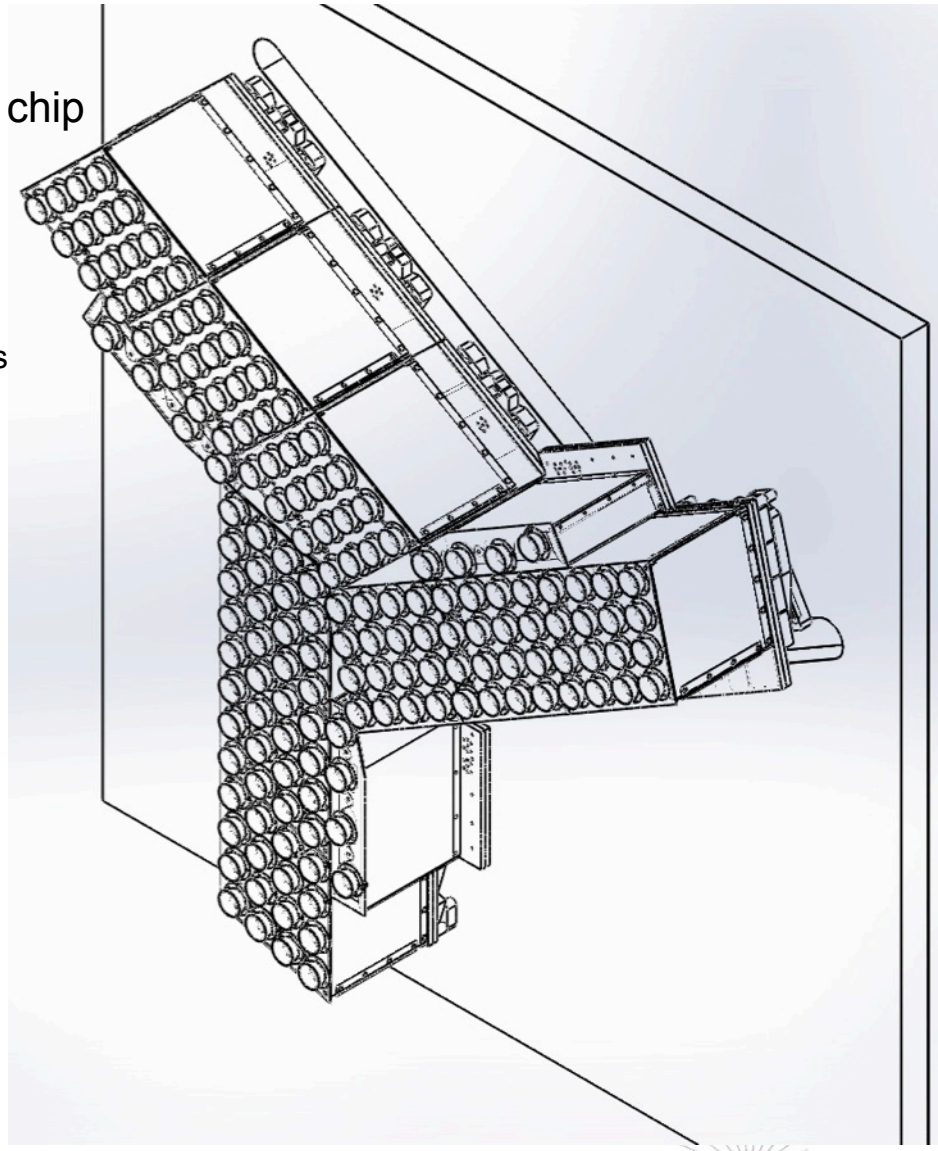
GeoSTAR IIP-10: Final phase

- Further testing of correlator ASIC
  - Complete full correlator board hosting new chip
  - Full functional testing of new chip
- System testing
  - Assemble small 183-GHz antenna array
    - Using miniature ultra-low-power MIMRAM receivers
  - Integrate full system with correlator
  - Characterize system performance
  - Imaging demonstration





What can we do with GeoSTAR?

TIME TESTED MEASUREMENTS AND DATA PRODUCTS USING MATURE ALGORITHMS

GeoSTAR will make similar measurements from GEO as AMSU currently does from LEO, but every 15 minutes vs. 2 times per day

High-intensity events can be sampled in 5 minutes or less

GeoSTAR will uniquely provide measurement of
Temperature/moisture/clouds; Wind; Precipitation
simultaneously, continuously and in 3 dimensions

Parameter	Horizontal	Vertical	Temporal	Precision	Accuracy	Thermodyn.	Microphys.	Dynamics
Brightness temperatures	25 - 50 km	N/A	5-20 min.	0.5-1.5 K	0.5 K			
Temperature	25 - 50 km	2-3 km	10-20 min	1.5-2.5 K	0.5 K	√		
Water vapor				25-40%	10%	√		
Wind vector (u,v)				8 m/s	2 m/s			√
Reflectivity				4-6 dBZ	2 dBZ		√	
Rain rate		N/A		5 mm/hr	2 mm/hr	√	√	
LWP				25%	10%	√		
IWP				25%	20%	√	√	

Precision & accuracy reflect performance of MIRS (except for reflectivity)

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Pre-PATH mission

We are approaching readiness for space mission

Ready for Venture-class mission now

- Timeline: Start development ~2014 → Launch ~2018
- Objective: PATH science subset demonstrator
- Instrument: "GeoSTAR-lite" – all key technologies @ TRL 6
  - Correlator baseline: Omnisys 32x32 ASIC (TRL 6: has been rad tested) – meets science requirements

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Space Administration

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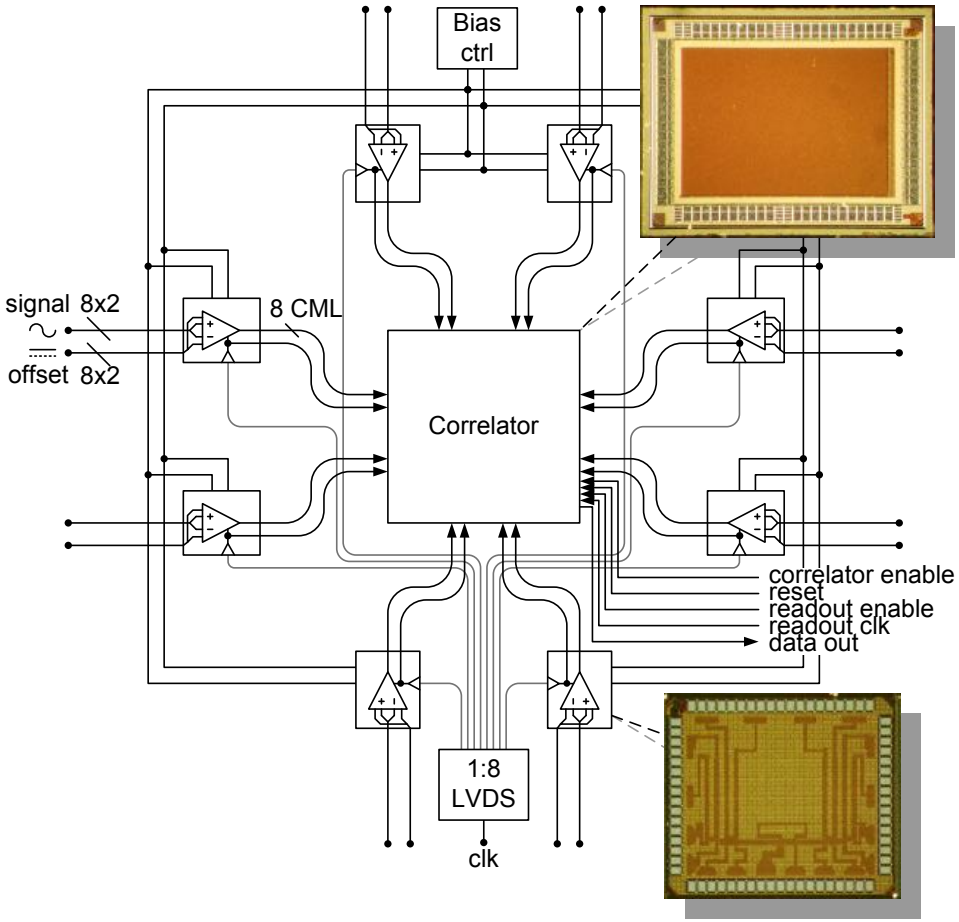
Pre-PATH mission

Swedish 32x32 correlator
Tested and verified



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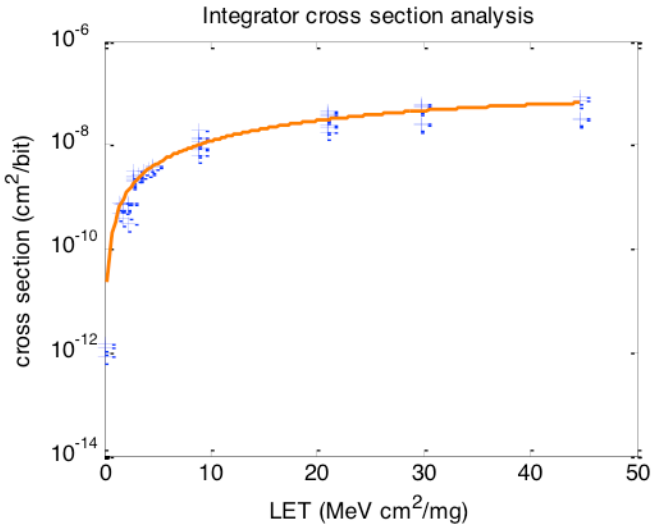
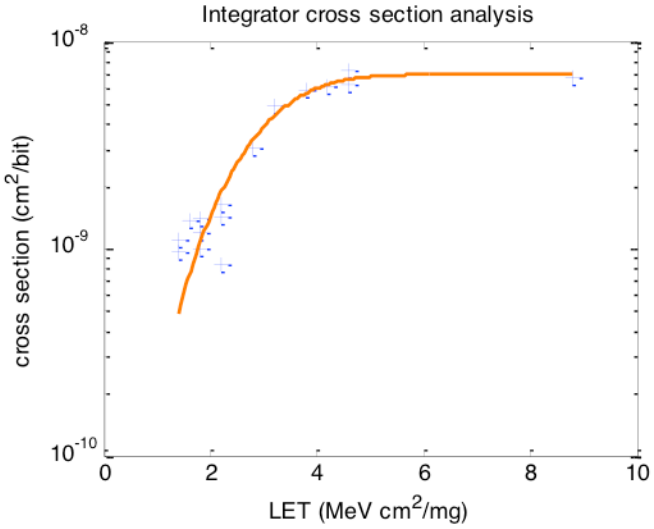
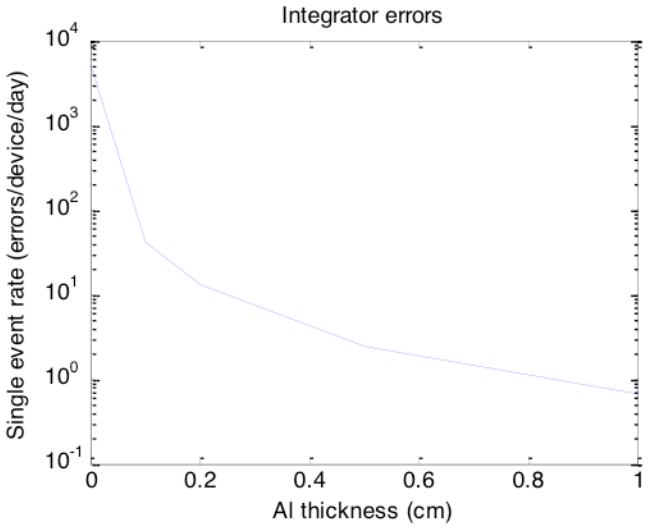
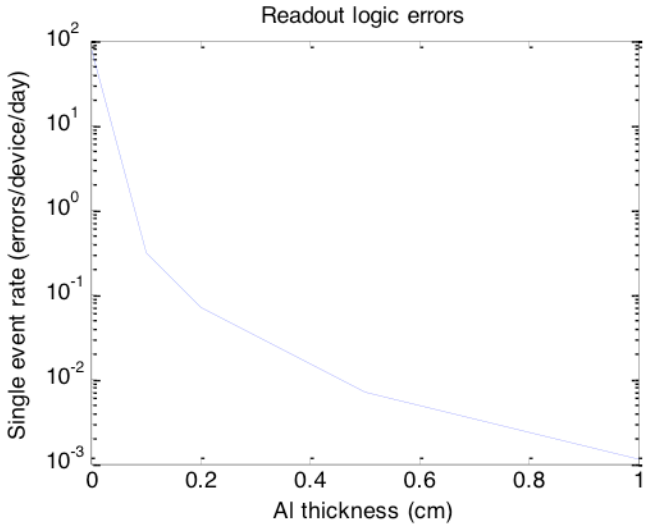
Pre-PATH mission

Radiation test results: No susceptibility of concern









Summary

- STAR concept demonstrated in IIP-03
  - Developed a functional 50-GHz STAR demonstrator
- Key technologies developed in IIP-07
  - Developed miniature low-power 183-GHz MMIC receivers
  - Developed new alias-rejecting antenna array design
- Ready for PATH mission after IIP-10
  - Full-size 64x64 correlator ASIC is a success!
  - Can start development ~2015 → launch ~2020

- We have advanced the technology from Tier-3 level to Tier-1 level – a major achievement