The Lunar Mini-RF Radars and their Hybrid-Polarimetric Architecture

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The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Hybrid-Polarity SAR
- Self-Calibration
- Mini-RF Lunar Radars
- Results
- Conclusions

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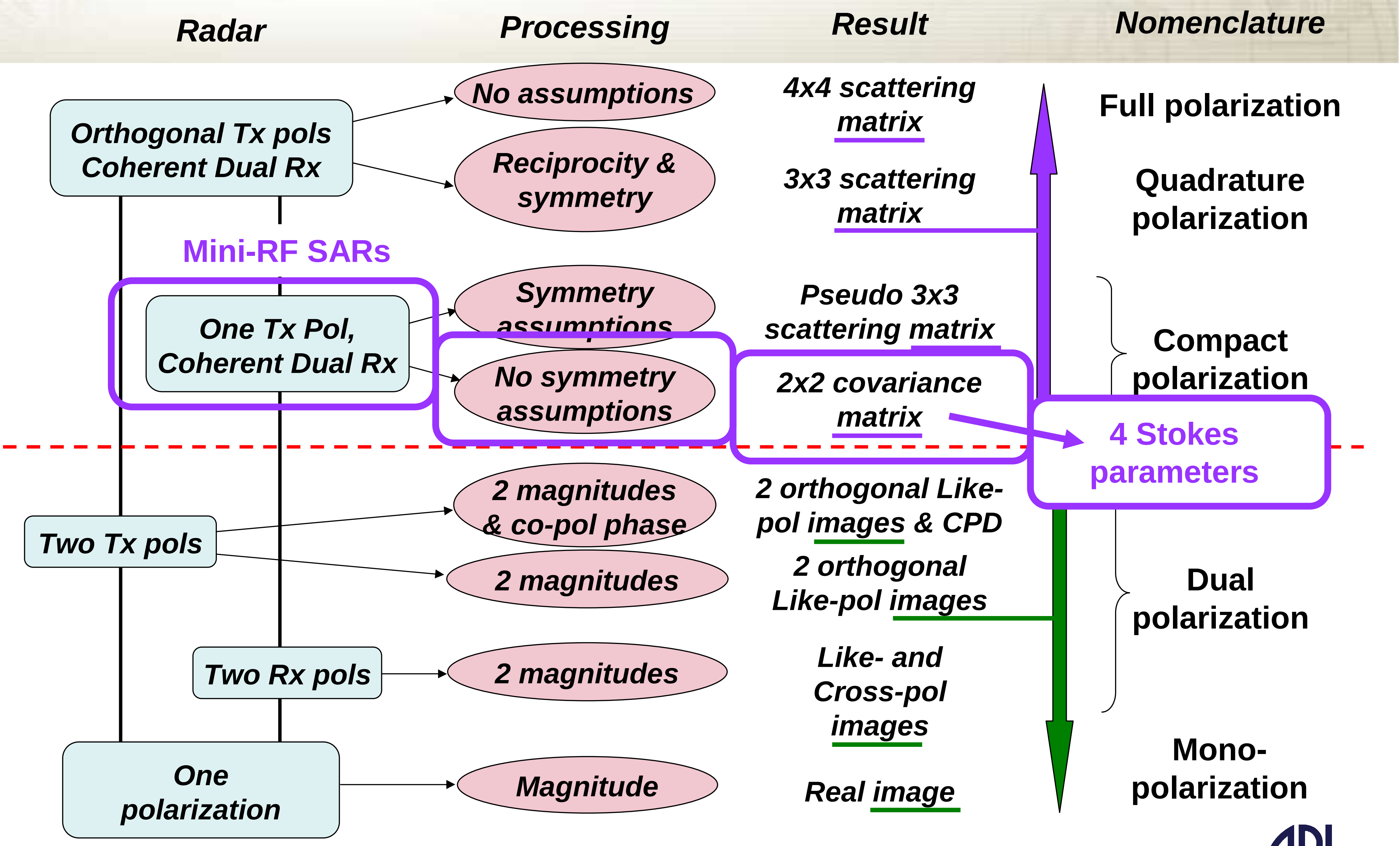
Polarimetric Imaging Radar Hierarchy



Radar | **Processing** | **Result** | **Nomenclature**

Orthogonal Tx pols Coherent Dual Rx

No assumptions → *4x4 scattering matrix* → **Full polarization**

Reciprocity & symmetry → *3x3 scattering matrix* → **Quadrature polarization**

Mini-RF SARs

One Tx Pol, Coherent Dual Rx

Symmetry assumptions → *Pseudo 3x3 scattering matrix* → **Compact polarization**

No symmetry assumptions → *2x2 covariance matrix* → **4 Stokes parameters**

Two Tx pols

2 magnitudes & co-pol phase → *2 orthogonal Like-pol images & CPD* → **Dual polarization**

2 magnitudes → *2 orthogonal Like-pol images*

Two Rx pols → *2 magnitudes* → *Like- and Cross-pol images*

One polarization → *Magnitude* → *Real image* → **Mono-polarization**

Polarization Bases for Lunar SAR

Requirements

Transmit circular polarization

Measure (*at least*) circular polarization ratio (CPR)

Minimize on-board radar mass, parts, etc.

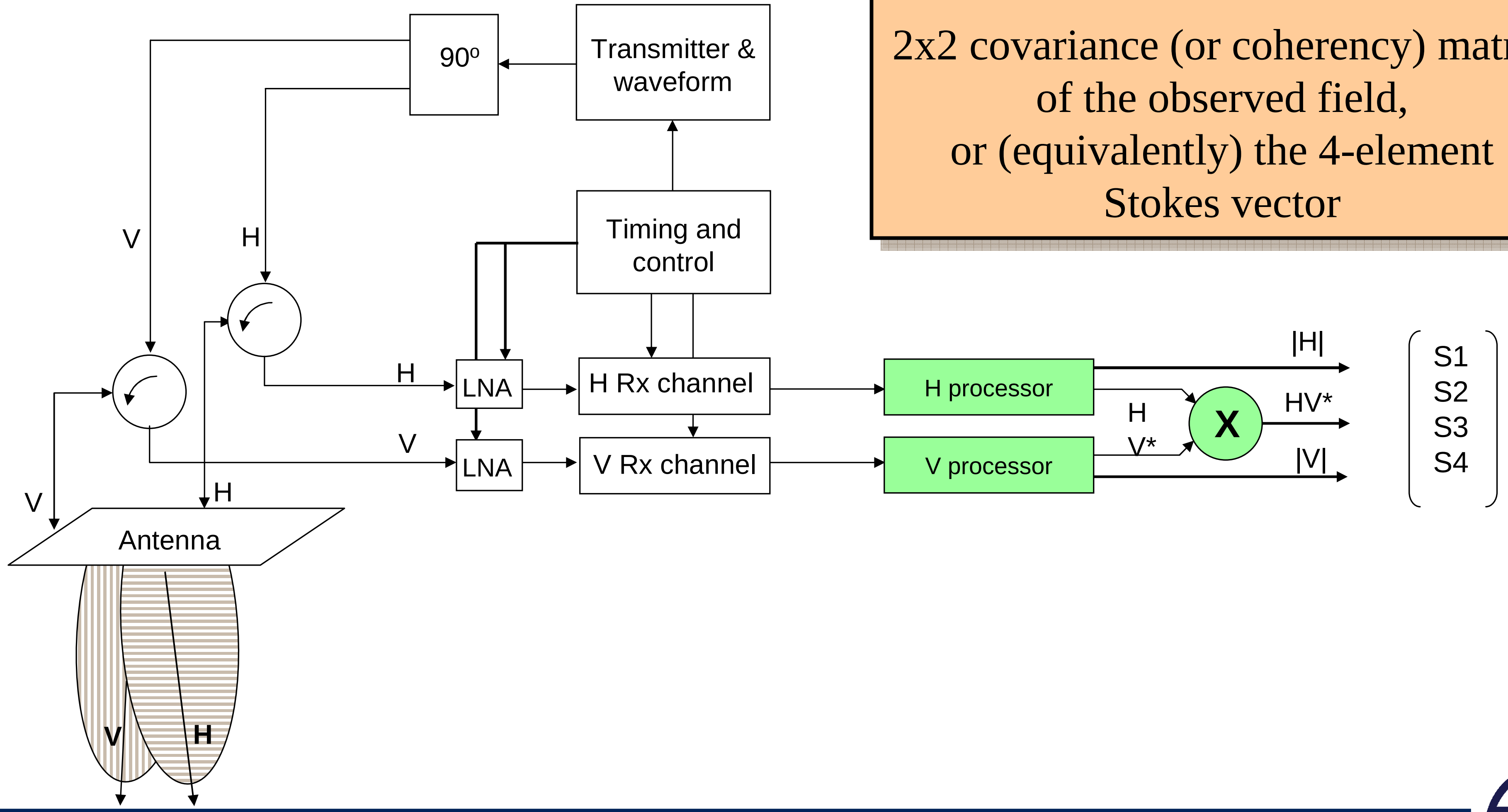
Optimize remote calibration w/o corner reflector

Leads to **Hybrid-Dual-Polarity**

Receive orthogonal linear polarizations (*e.g.* H and V)

Coherent on receive (retain H/V phase)

Dual Hybrid-Polarimetric Architecture



Primary data product:

2x2 covariance (or coherency) matrix of the observed field, or (equivalently) the 4-element Stokes vector

The Hybrid Dual-Polarimetric Architecture

Transmit circular polarization. Then

- ✓ The Stokes parameter values are independent of the polarization basis of the dual receivers
- ✓ Therefore, a linear basis on receive enjoys equivalent information content as classical circular receive polarity

	CL Hybrid Polarity		Circular/Circular
S_1	$= \; < \lvert E_H\rvert^2 + \lvert E_V\rvert^2 > + \, 2\, N_o$	$=$	$< \lvert E_R\rvert^2 + \lvert E_L\rvert^2 > + \, 2\, N_o$
S_2	$= \; < \lvert E_H\rvert^2 - \lvert E_V\rvert^2 >$	$=$	$2\,\mathrm{Re} < E_R E^*_L >$
S_3	$= \; 2\,\mathrm{Re} < E_H E^*_V >$	$=$	$2\,\mathrm{Im} < E_R E^*_L >$
S_4	$= \; -\, 2\,\mathrm{Im} < E_H E^*_V >$	$=$	$- < \lvert E_R\rvert^2 - \lvert E_L\rvert^2 >$

Stokes "Child" Parameters

Selected examples

Degree of polarization

$$m = (S_2^{\,2} + S_3^{\,2} + S_4^{\,2})^{1/2} / S_1$$

Fundamental; 1:1 mapping
wrt **Entropy** E
$E \sim (1 - m^2)^{\gamma}$, $\gamma \sim 0.74$

Circular polarization ratio

$$\boldsymbol{\mu}_C = (S_1 - S_4) / (S_1 + S_4)$$

Indicator of scattering associated with planetary ice deposits or dihedrals: $\boldsymbol{\mu}_C > \sim 0.5$
(Generalizes to elliptical pol)

Relative phase $\delta = \arctan(\,-\,S_4 / S_3\,)$

Sensitive indicator of "double bounce" backscattering, rotationally invariant *iff* CP Tx

Ellipticity $\boldsymbol{\mu}_E = -\,S_4 / S_1$

Gentle transition from perfect circular polarization to elliptical (*near-unity axial ratio*)

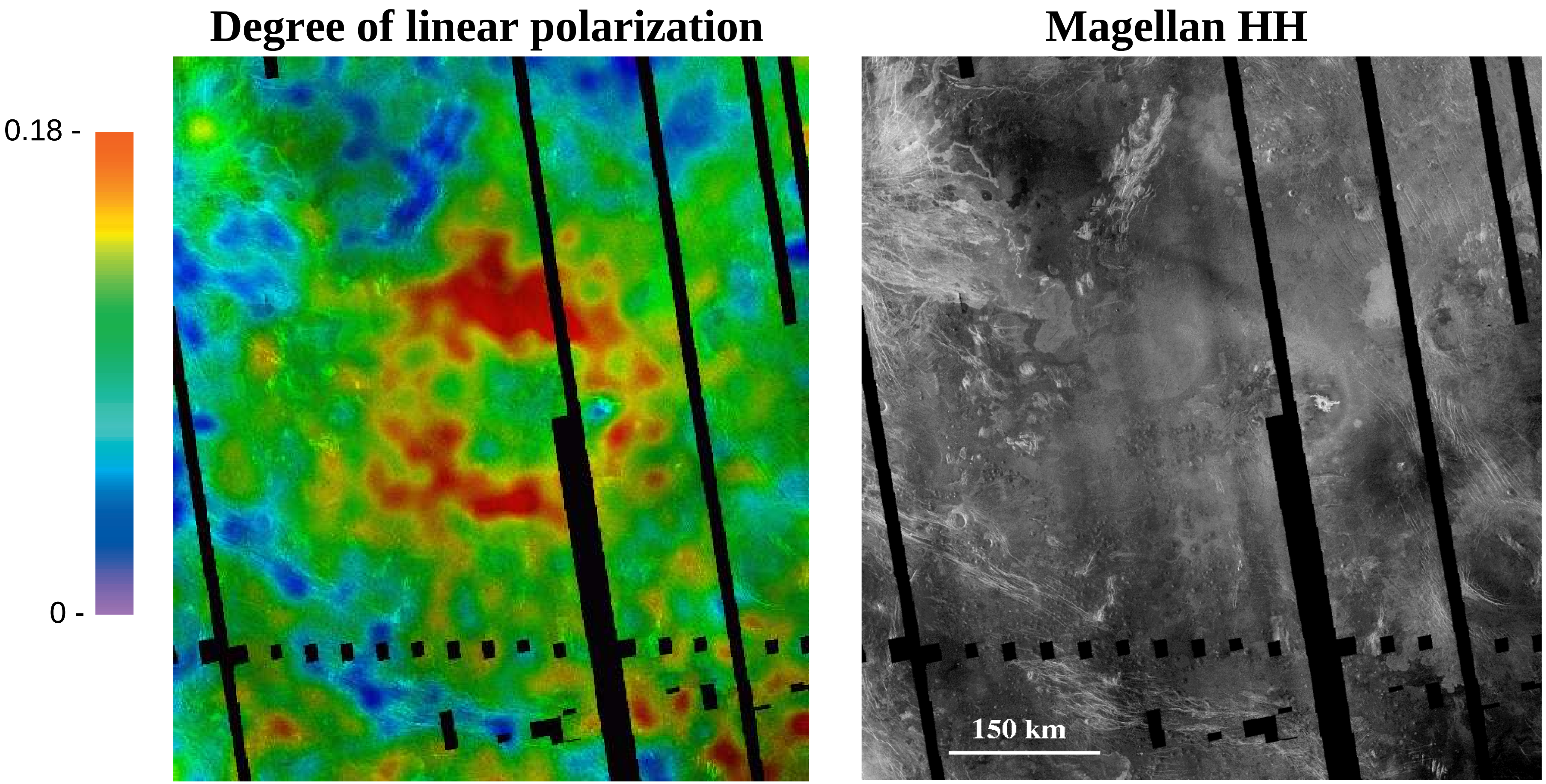
The Arecibo Facility

Arecibo radio/radar telescope, important contributions from the early 1960s

Coherent, circularly dual polarized

Major observations from early 1990’s have been coherent dual polarized

Mapping Surface Overburden with μ_L

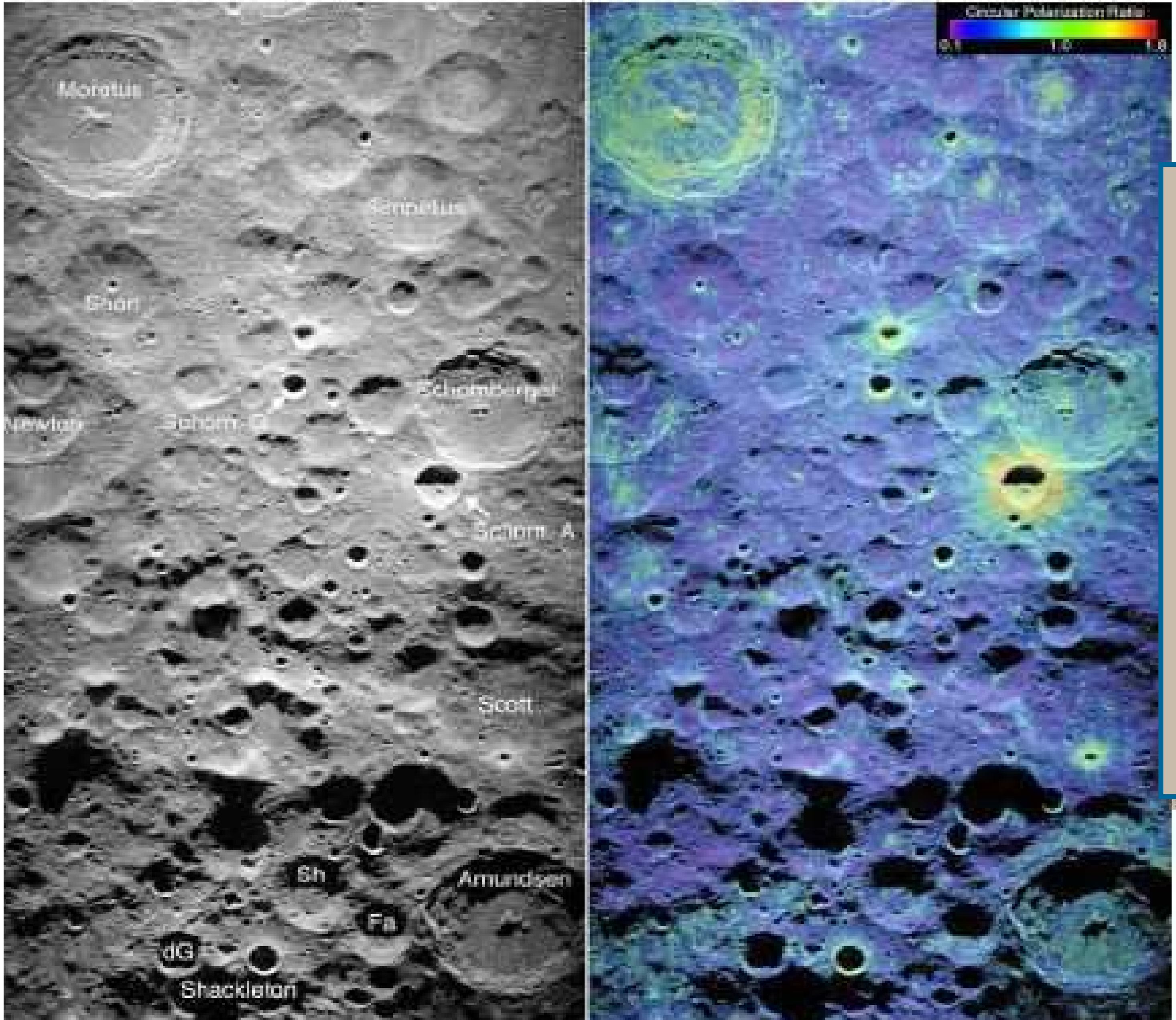

Degree of linear polarization

Magellan HH

The *degree of linear polarization* indicates volume and interface surface backscatter (crater Nelike on Venus).

(Reproduced with permission, courtesy L. Carter).

Circular Polarization Ratio (CPR)



Lunar South Polar region

Arecibo-Green Bank S-band (13-cm) Dual-circular polarization, delay-Doppler, Stokes parameter analysis. (2005)

From Campbell, Campbell, Carter, Margot, and Stacy, et al., *NATURE* 443, 835-837 (19 Oct 2006)

Agenda

- Hybrid-Polarity SAR
- **Self-Calibration**
- Mini-RF Lunar Radars
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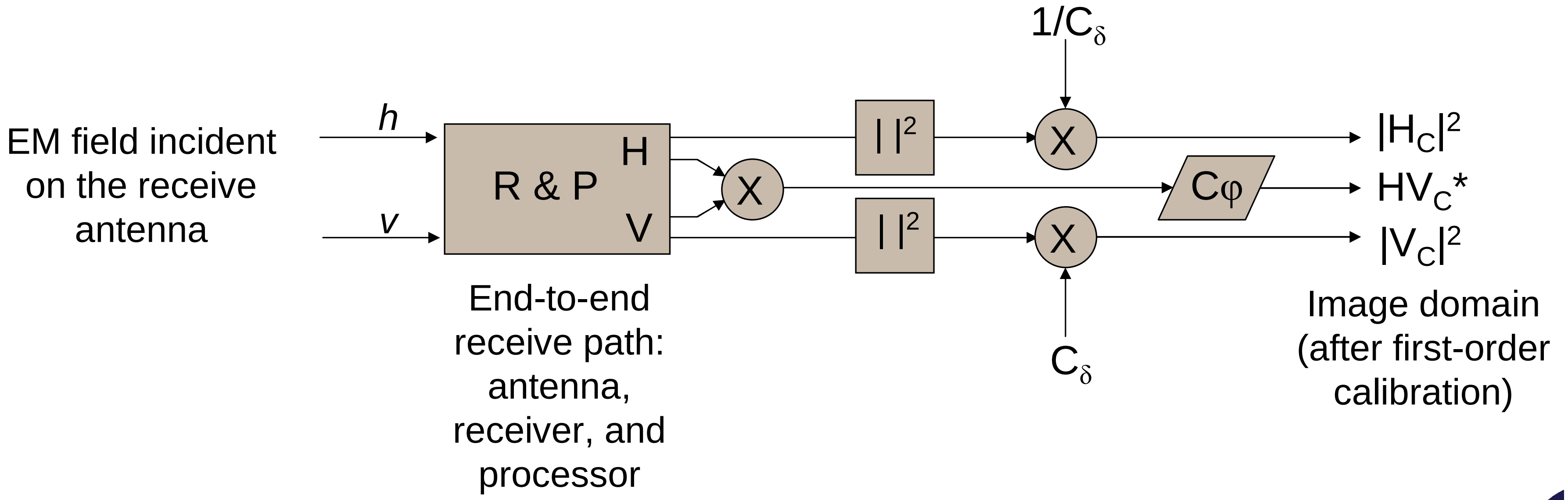
Calibration Advantages Unique to Hybrid Polarity

- **Relatively comparable (mean) signal levels in both channels under all viewing conditions – *No "cross-polarized" side***
- **When nadir viewing (scatterometer mode), <CH> should be statistically identical to <CV> to first and second order**
- **Observed discrepancies => 1st order calibration coefficients**
- **Hence, hybrid-polarity supports relative "self-calibration"; receive paths can be balanced using normal lunar data without need of corner reflectors**
- **If near-perfect CP transmitted, then nadir data are necessary and sufficient for end-to-end (Tx & Rx) relative calibration**
- **If not, then external reference (e.g. Arecibo) required**

Objective: to Balance the Entire Receiver Chain

- **Measure V/H magnitude imbalance; V − H phase difference**
- **Leads to calibration coefficients Cδ and Cφ**
- **Result? Rx end-to-end: H gain ≡ V gain & V − H phase = 0**
- *Aside: there remain variations wrt T, antenna patterns, etc.*



Methodology: Relative Self Calibration (1/3)

Nadir viewing: Backscatter on average will be a reflection of the transmitted field, thus opposite sense circularly polarized (90-degree H/V phase & |H| = |V|)

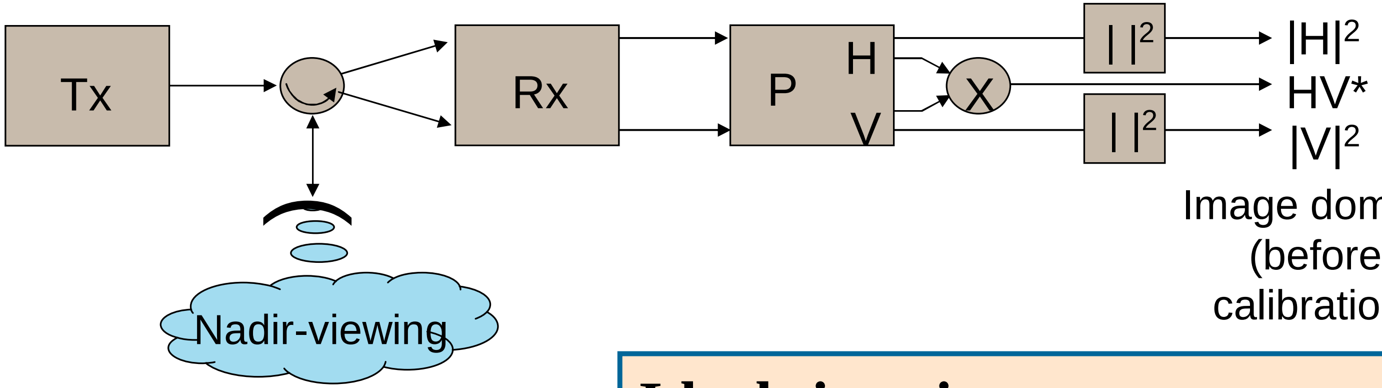


Image domain (before calibration)

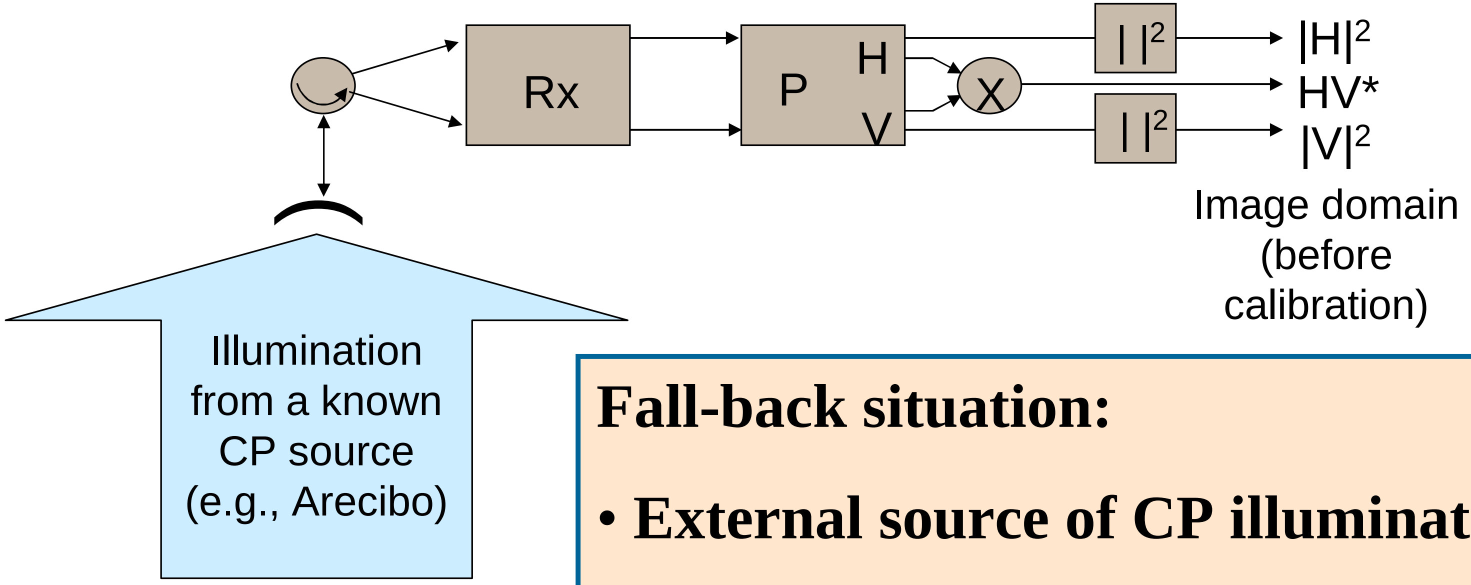
Raw signal domain, backscatter from the "scatterometer" mode

Ideal situation:

- **Circular transmit polarization**
- **Receive chain imbalances directly observable in the processor's cross-product data**

Methodology: Relative Self Calibration (2/3)

Known source: Excite radar receive chain by circular polarization (90-degree H/V phase & |H| = |V|)

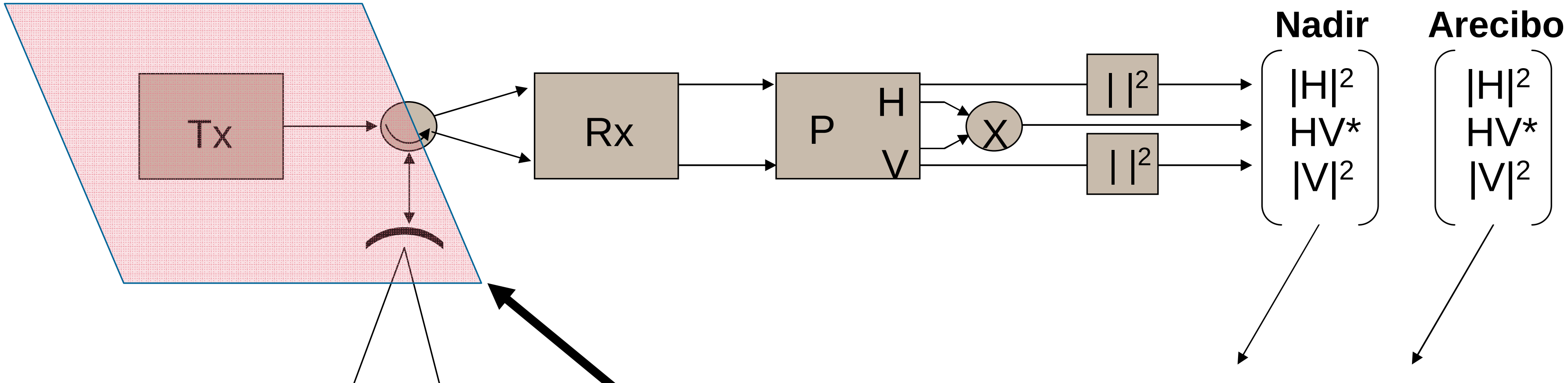


Fall-back situation:

- **External source of CP illumination**
- **Receive chain imbalances directly observable in the processor's cross-product data**

Methodology: Relative Self Calibration (3/3)

Results from nadir-viewing and external CP illumination are sufficient to characterize the axial ratio of the transmitted EM field



Nadir backscatter
(receive and transmit paths)

AND

external CP from **Arecibo**
(receive paths only)

Transmit axial ratio may be found directly from the differences in amplitude and phase balances seen in Nadir *and* Arecibo observations

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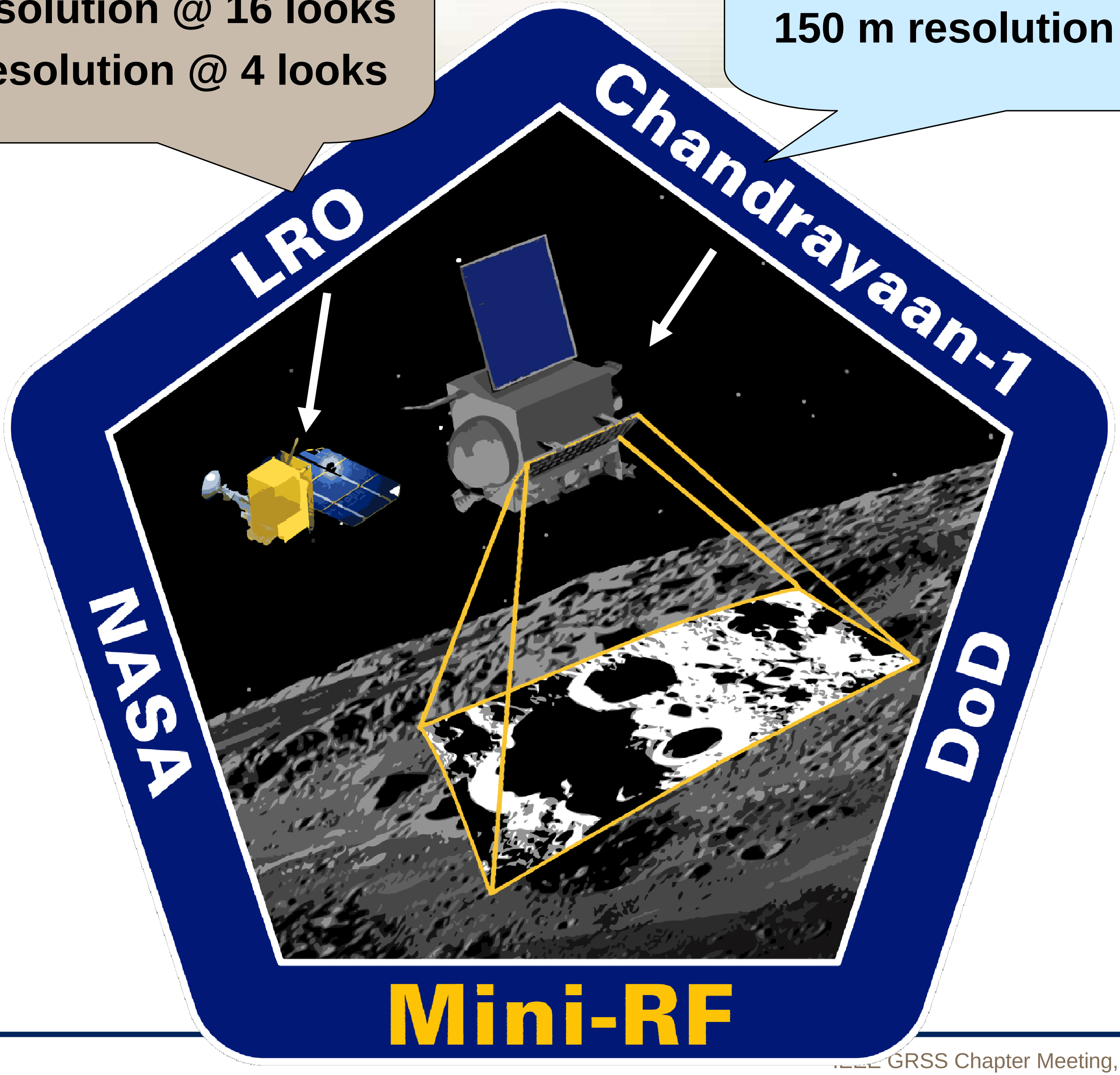
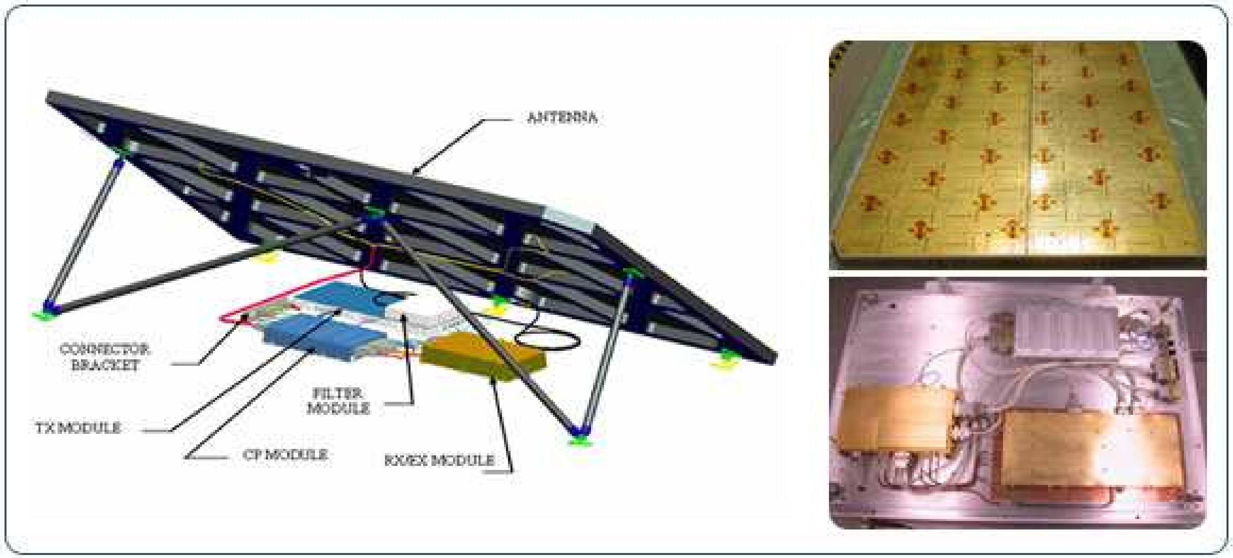
Launch 17 June 2009 (+)
S- & X-band (12 cm & 4 cm)
150 m resolution @ 16 looks
& 15 m resolution @ 4 looks

Launched 22 Oct 2009
S-band (12 cm wavelength)
150 m resolution @ 16 looks



Mini-SAR (*on Chandrayaan-1*)



High-Level Specifications

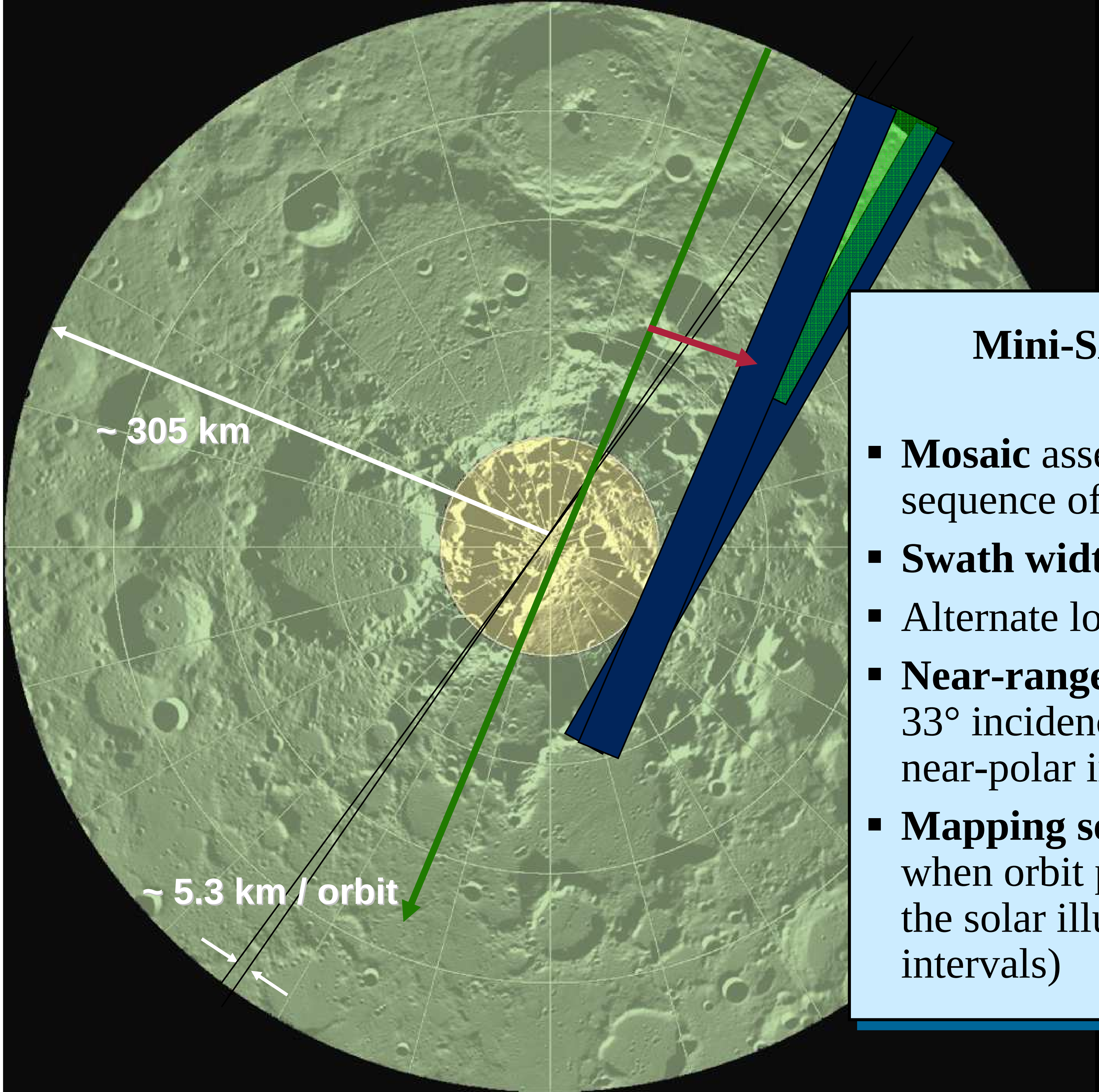
- **Antenna: 1.8 m x 0.7**
- **Mass: ~9 kg**
- **DC Power: 85 W**
- **Tx power (Avg): 11 W**

Externally mounted, covered by thermal blanketing

Typical operating temperatures:

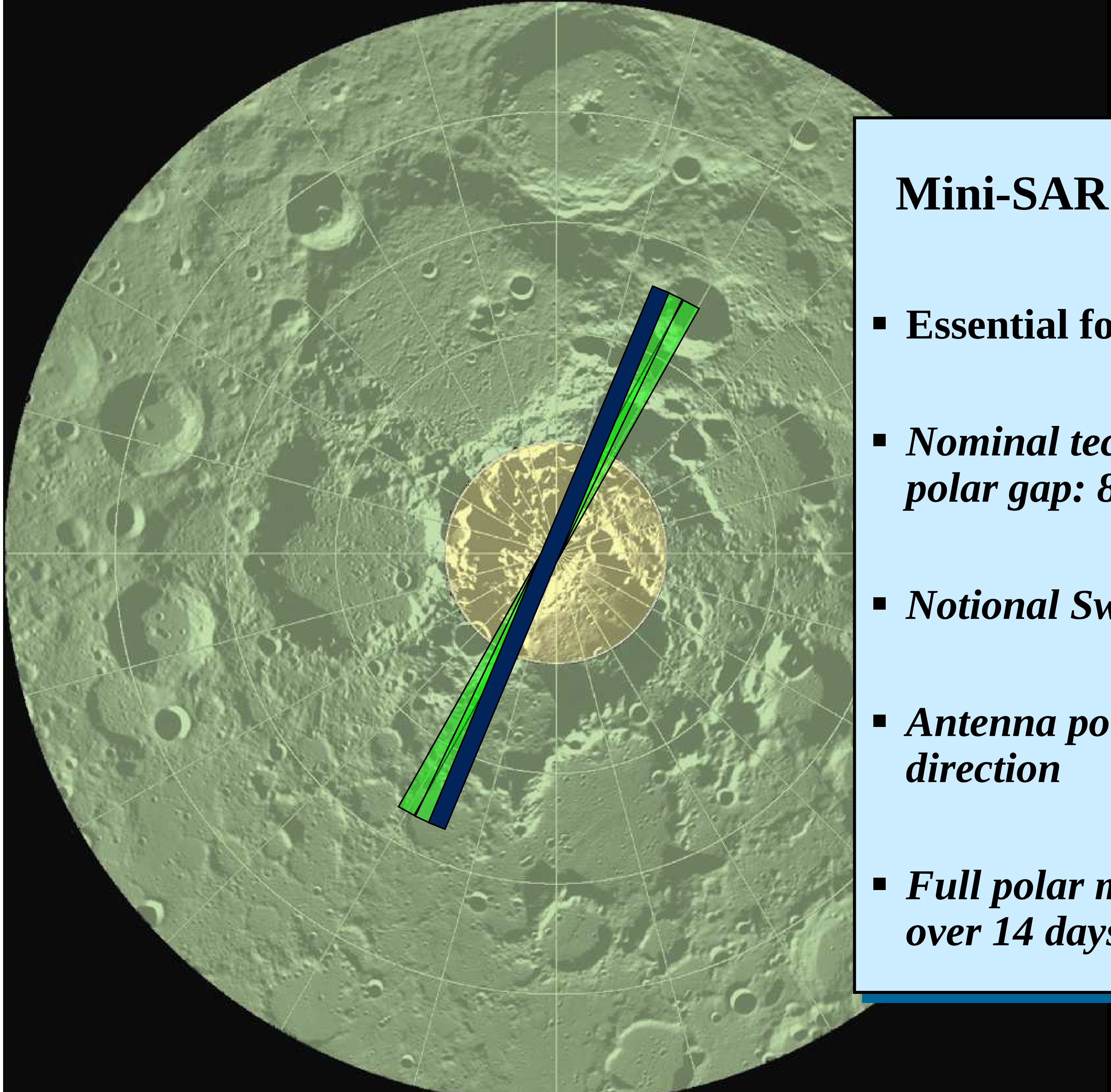
Antenna: -30° C

Electronics: + 35° C



Mini-SAR Mapping

- **Mosaic** assembled from a sequence of ~338 orbit strips
- **Swath width** 8 km
- Alternate long and short passes
- **Near-range** minimum is set by 33° incidence & altitude => near-polar image **gap**
- **Mapping seasons** of ~ 40 days when orbit plane orthogonal to the solar illumination (6 month intervals)

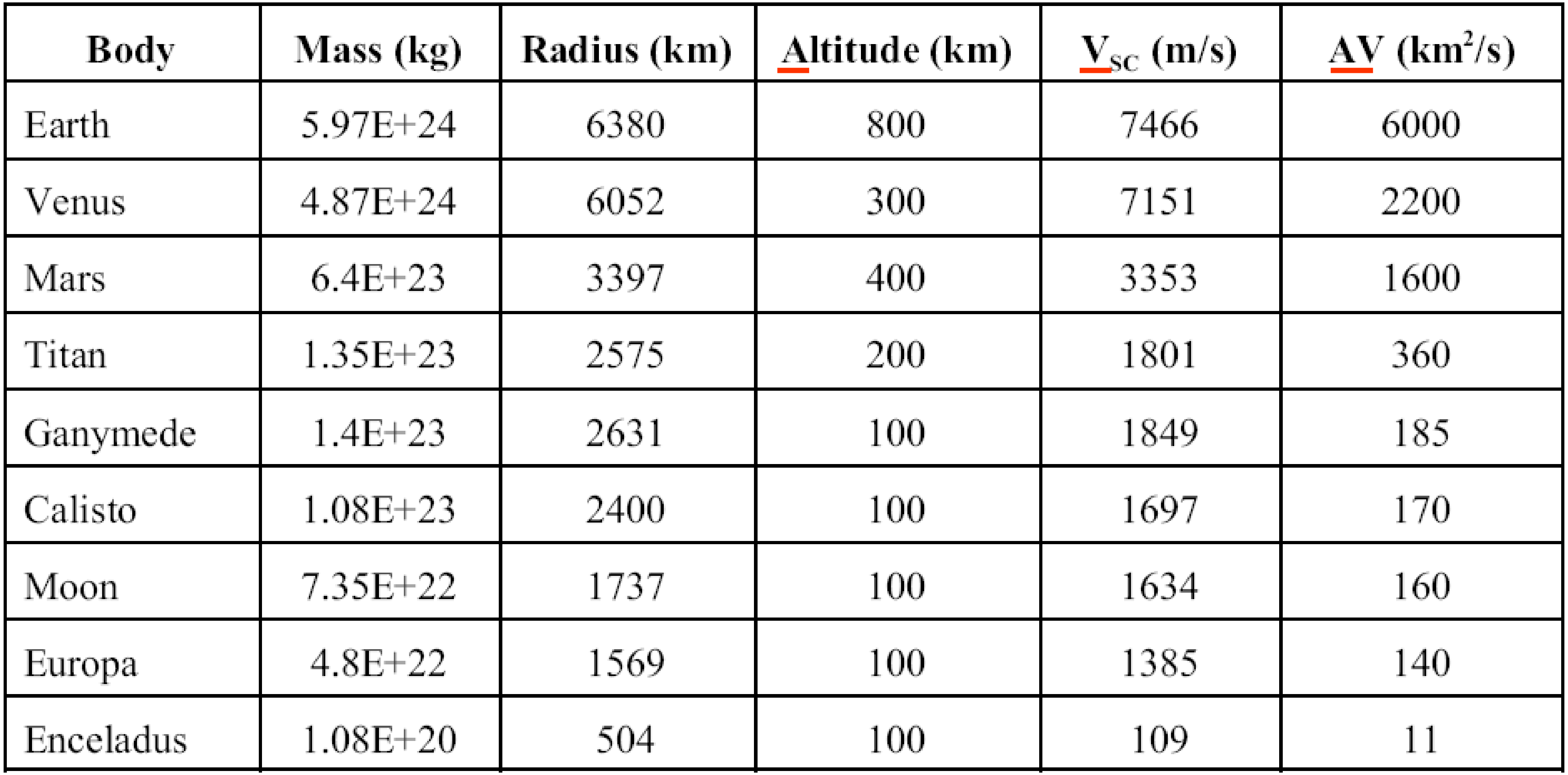


Mini-SAR Scatterometry

- **Essential for self-calibration**
- ***Nominal technique to fill in polar gap: 85°-90°-85°***
- ***Notional Swath Width: 10 km***
- ***Antenna pointed in nadir direction***
- ***Full polar mosaic acquired over 14 days***

Spacecraft Velocities and the AV Scaling Factor

"Mini"?: *SAR Antenna Area and (usually) Mass are proportional to AV*



Body	Mass (kg)	Radius (km)	Altitude (km)	V_{SC} (m/s)	AV (km^2/s)
Earth	5.97E+24	6380	800	7466	6000
Venus	4.87E+24	6052	300	7151	2200
Mars	6.4E+23	3397	400	3353	1600
Titan	1.35E+23	2575	200	1801	360
Ganymede	1.4E+23	2631	100	1849	185
Calisto	1.08E+23	2400	100	1697	170
Moon	7.35E+22	1737	100	1634	160
Europa	4.8E+22	1569	100	1385	140
Enceladus	1.08E+20	504	100	109	11

Universal gravity constant G = $6.67 \times 10^{-11}\ Nm^2kg^{-2}$

$$V_{sc} = \sqrt{M_P G / (R_P + h)}$$

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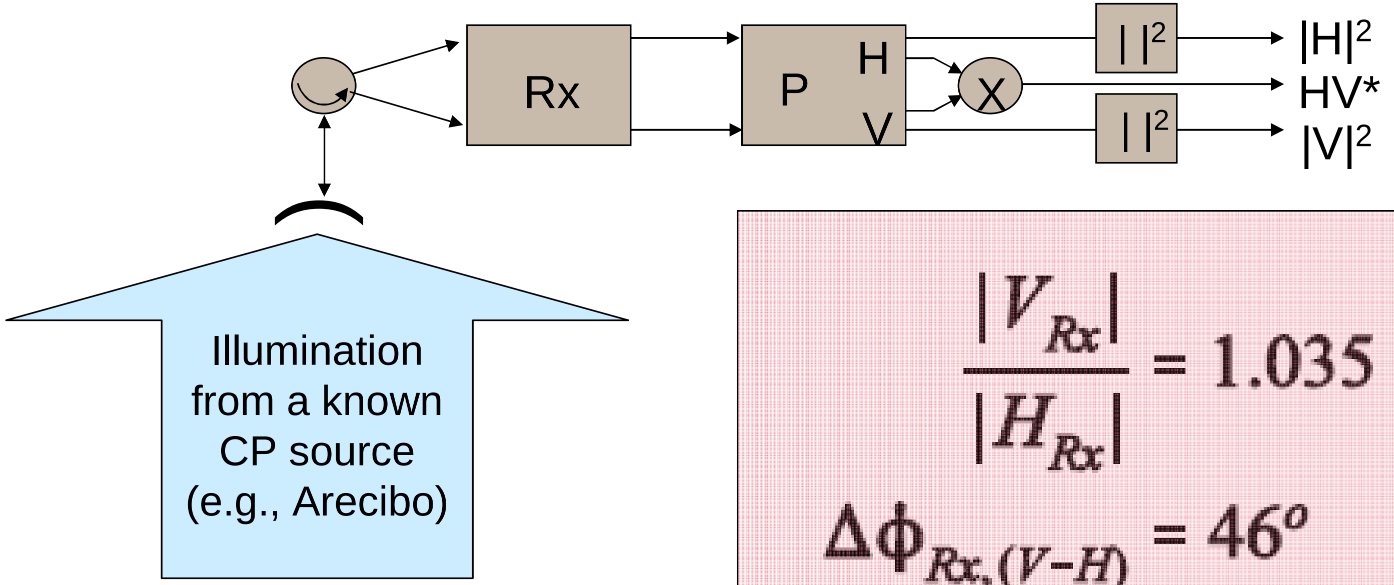
Relative Calibration Results: Arecibo*

Known source: Excite radar receive chain by circular polarization (90-degree H/V phase & |H| = |V|)



Illumination from a known CP source (e.g., Arecibo)

$$\frac{|V_{Rx}|}{|H_{Rx}|} = 1.035$$

$$\Delta\phi_{Rx,(V-H)} = 46^o$$

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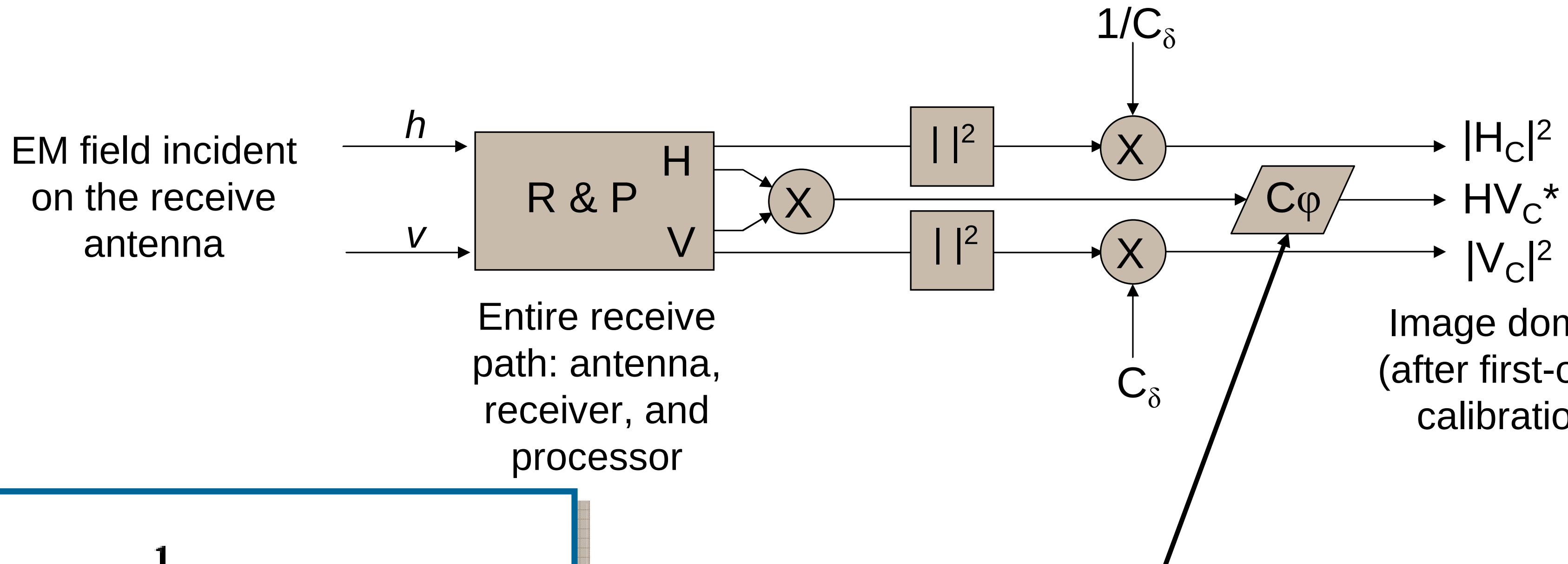
* H Sequeira, “Calibration Experiment with Arecibo Radio Telescope (ART)”, JHUAPL Internal Report SER-09-010, 05 March 2009.

Results: Receive chain calibration coefficients

Objective: find Cδ and Cφ to "perfectly" balance the receiver



$$\mathrm{Re}\,HV_C^* = \mathrm{Re}\,HV^*\cos C_\phi - \mathrm{Im}\,HV^*\sin C_\phi$$

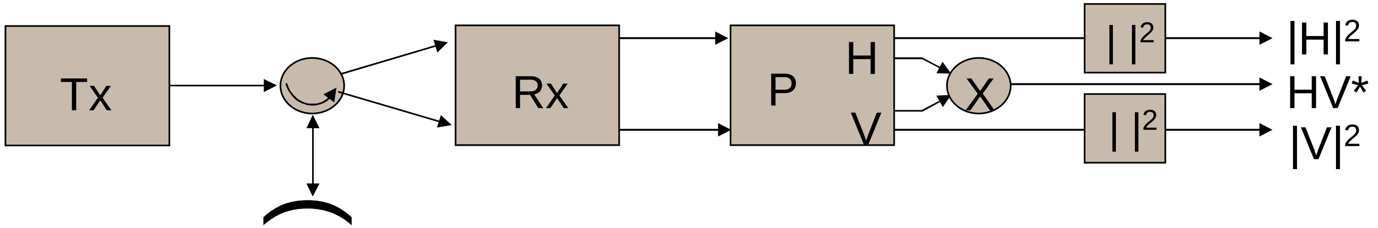
$$\mathrm{Im}\,HV_C^* = \mathrm{Re}\,HV^*\sin C_\phi + \mathrm{Im}\,HV^*\cos C_\phi$$

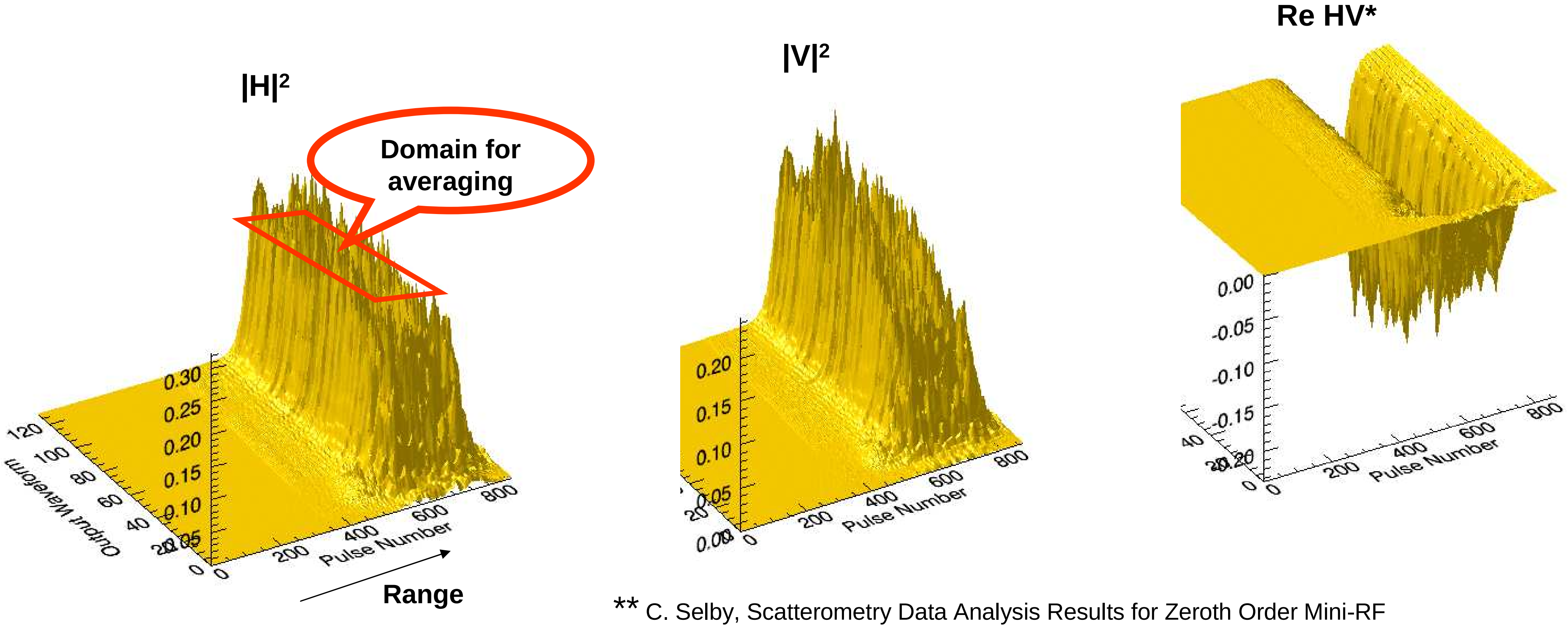
$$C_\delta = \frac{1}{\left(V_{Rx}/H_{Rx}\right)} = \mathbf{0.966}$$

$$C_\phi = \Delta\phi_{Rx,(V-H)} = 46^o$$

Arecibo measurements

Relative Cal^{n} Results: Scatterometer** (1/2)

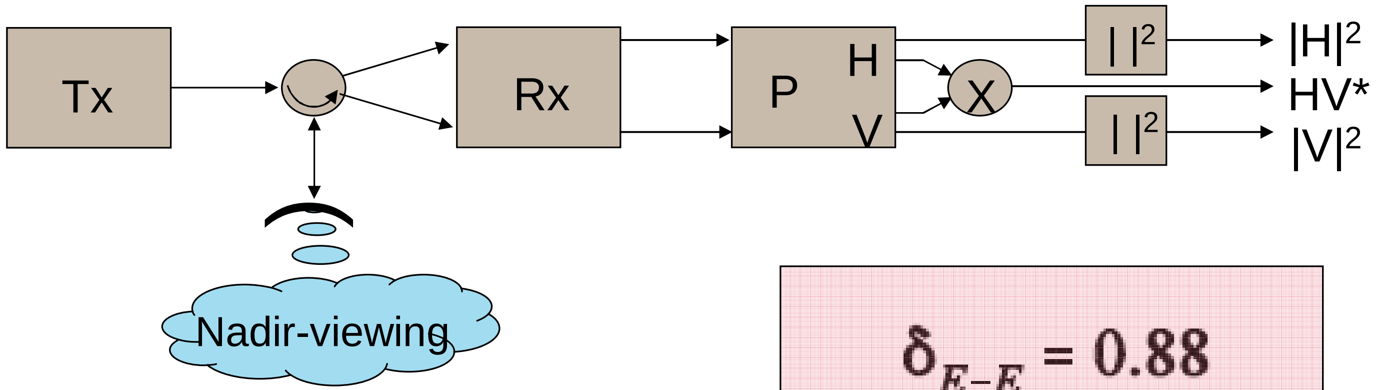




** C. Selby, Scatterometry Data Analysis Results for Zeroth Order Mini-RF Calibration, JHU/APL Internal Report, SIS-09-007, April 20, 2009.

Results: Scatterometer** (2/2)

Nadir viewing: Backscatter on average will be a reflection of the transmitted field, thus opposite sense circularly polarized (90-degree H/V phase & |H| = |V|)

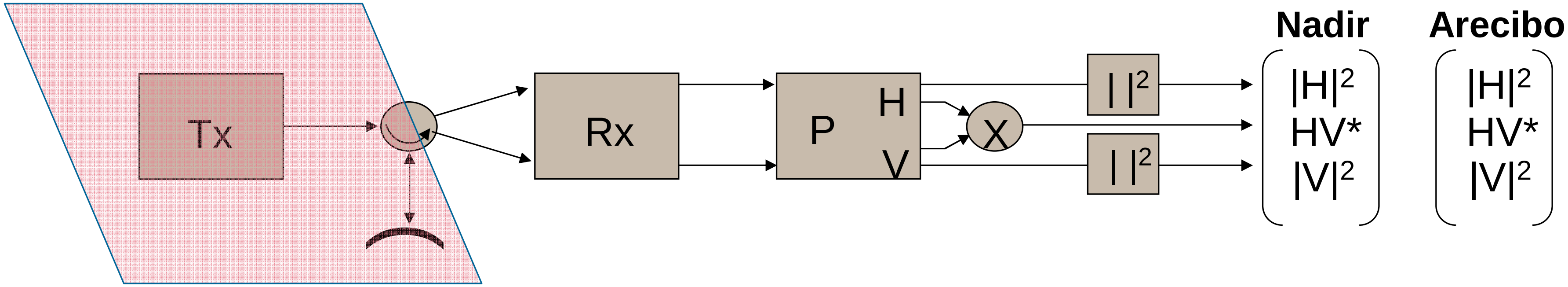


Raw signal domain, backscatter from the "scatterometer" mode

$$\delta_{E-E} = 0.88$$
$$\theta_{E-E} = 146^o$$

** C. Selby, Scatterometry Data Analysis Results for Zeroth Order Mini-RF Calibration, JHU/APL Internal Report, SIS-09-007, April 20, 2009.

Results: Transmitted Axial Ratio***



Derived transmitter amplitude imbalance A and relative phase δ

$$A = \frac{|V_{Tx}|}{|H_{Tx}|} = 0.85$$

$$\delta = \quad \phi_{Tx} = -100^o$$

Leads to an estimate of the axial ratio

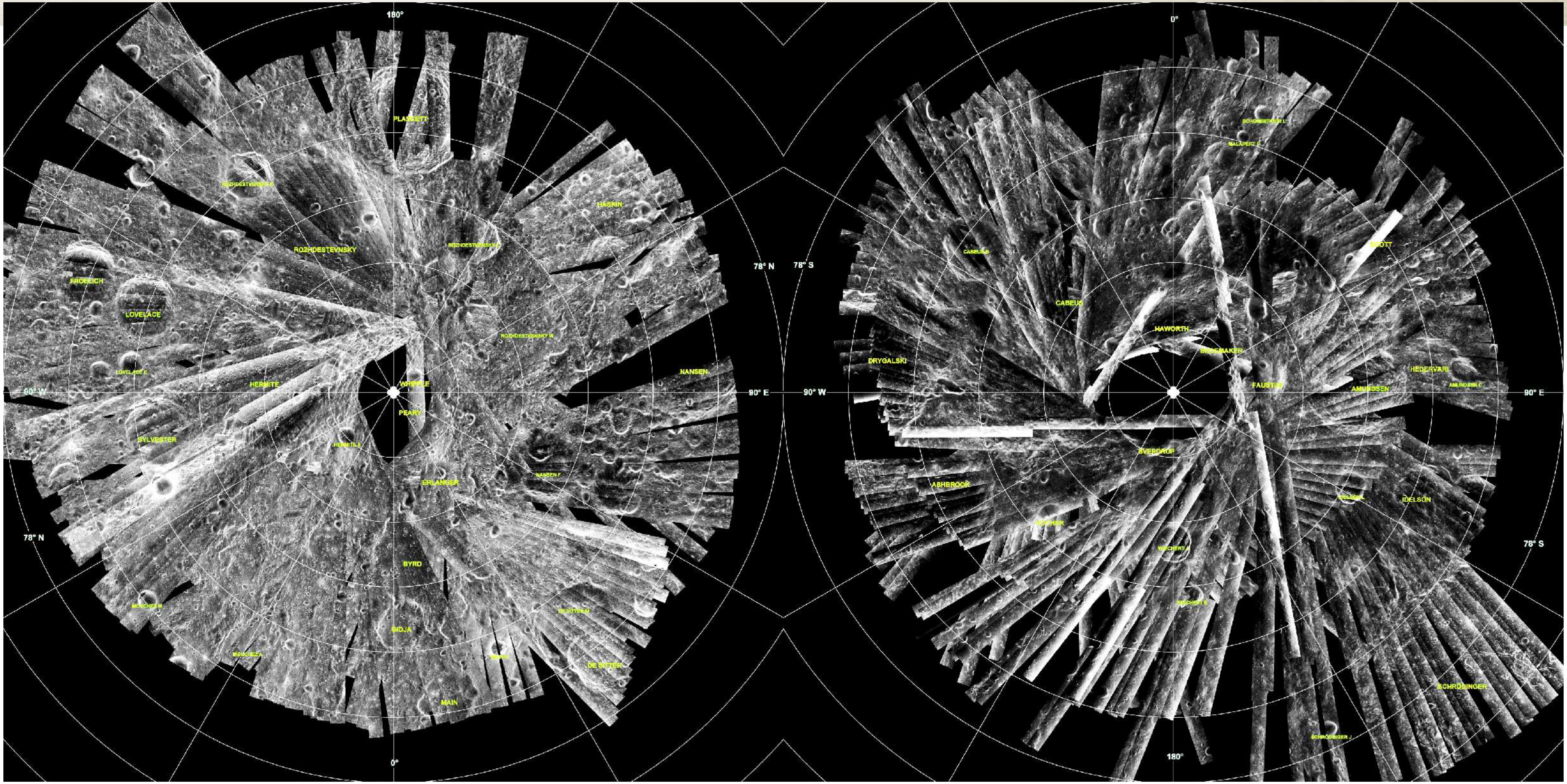
$$AR = 10\log[\cot^2(\chi)] = 2.08\ dB$$

using

$$\chi = \frac{1}{2}\sin^{-1}\left[\left(\frac{2A}{1+A^2}\right)\sin\delta\right]$$

***R. K. Raney, "End-to-end Forerunner relative calibration (top level)", JHUAPL Internal Report SRO-09M-11, 27 March 2009

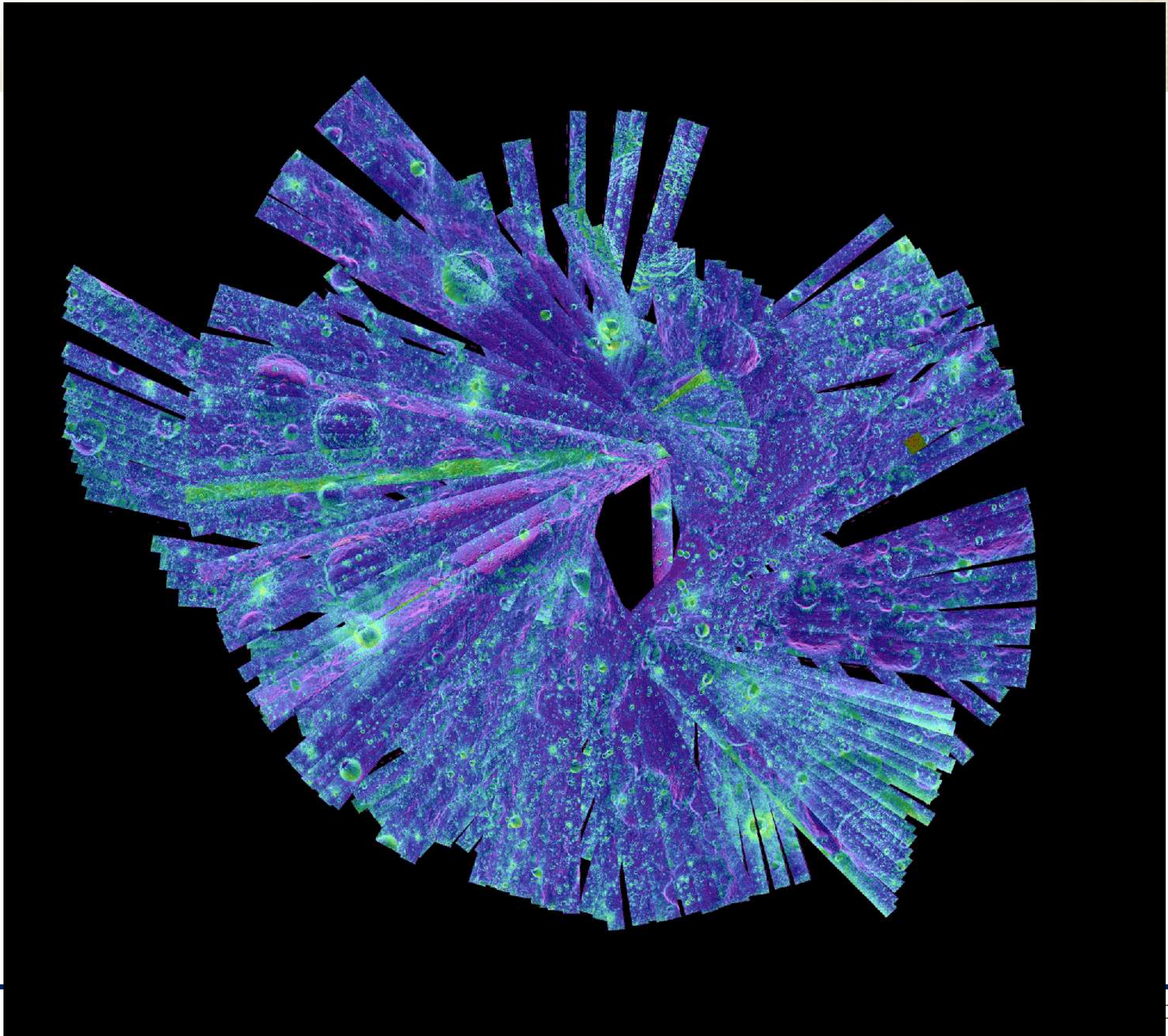
Mini-SAR Coverage as of April 16, 2009



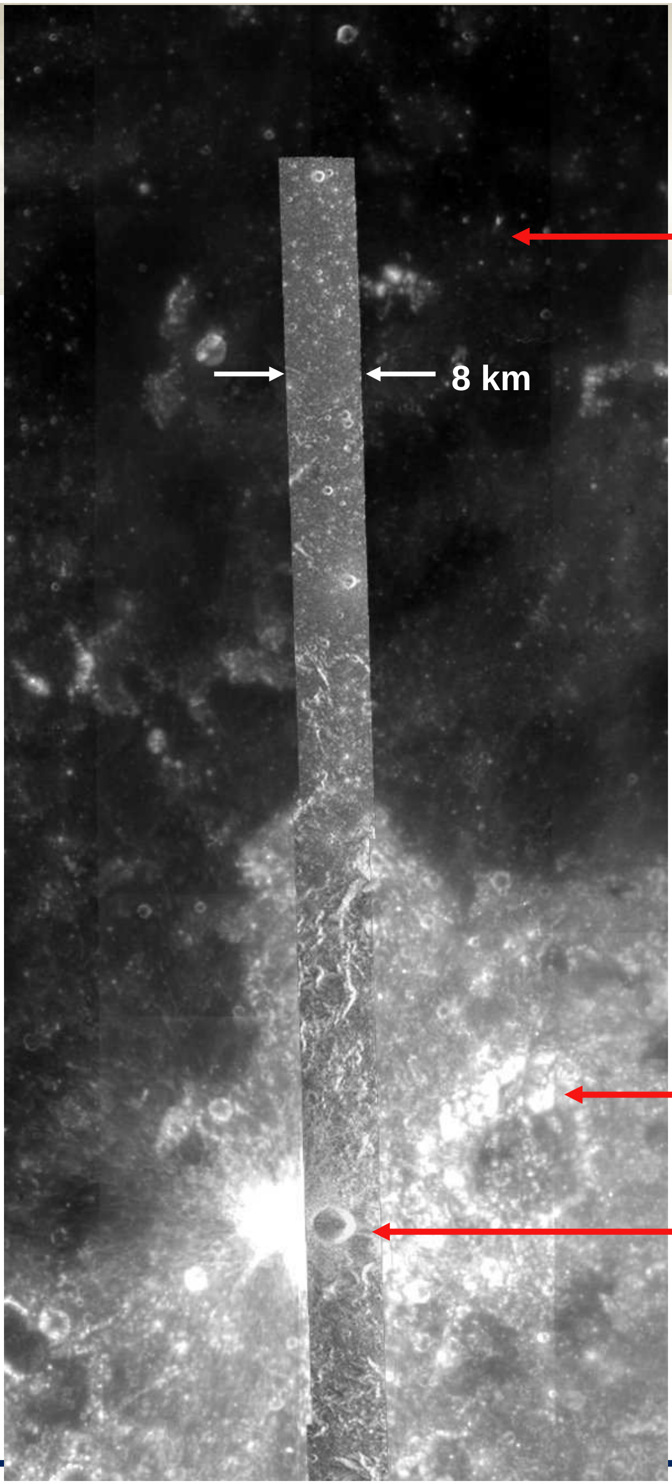
North Pole

South Pole

North Polar CPR Map (*before calibration*)



Circular Polarization Ratio Image



Mini-SAR strip on Clementine 750 nm base map

Mare Tranquillitatis

Mini-SAR Equatorial Calibration, 20 Jan. 2009

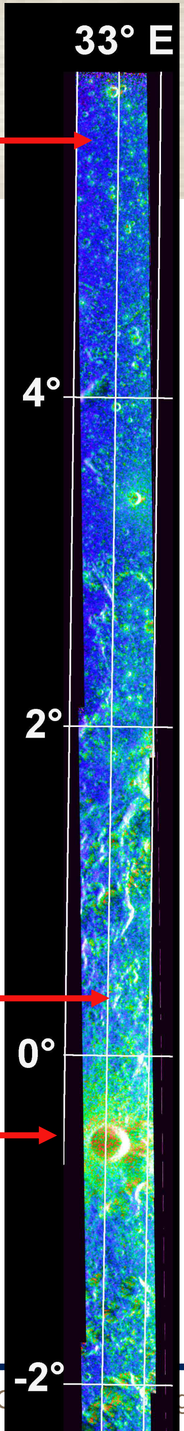
Objective: Collect SAR strip such that viewing geometry matched that of Earth-based radar imaging

Data successfully gathered along longitude 33° E, from 6° S to 6° N latitude

Nectaris basin highlands

Censorinus A

Courtesy, Dr. Paul Spudis, the Mini-SAR Science Team, and the Chandrayaan-1 Mission



CPR Scale

Blue < 0.3

Yellow > 0.8

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General Observations

- **Mini-RF operating well on Chandrayaan-1; very good first imaging season**
- **Next season starts in August 2009**
- **Coordination of mission operations through the Indian Space Research Organization (ISRO) is improving**
- **Initial Stokes parameter analyses very promising—"*The first orbiting radar astronomy observatory*"**
- **Mini-RF and Chandrayaan-1 science teams planning first set of papers, and initial release of data products**
- **Mini-RF data products will be submitted to the Planetary Data System (PDS)**
- **Lunar Reconnaissance Orbiter (LRO) ready for launch, with very good pre-launch Mini-RF I&T results**

Observations on Relative Calibration

- **Hybrid-polarity radar architecture supports relative self-calibration (*not possible with any other polarization plan*)**
- **Objective: calibration coefficients to render the receive chain "perfect" to 1st order (*equal H and V gains & zero V – H phase*)**
- **Nadir view (scatterometry mode) essential for relative polarimetric calibration**
- **For Mini-RF on Chandrayaan-1, an external circularly-polarized illumination source (Arecibo) was required**
- **Additional calibration steps to account for…**

  Antenna H and V pattern (range and azimuth) mis-match; Gain and/or phase variations with temperature; Spectral variations, etc

- **Advisable to repeat nadir and external observations to build confidence in the resulting first-order calibration coefficients**