Mini-RF on LRO and Arecibo Observatory Bistatic Radar Observations of the Moon

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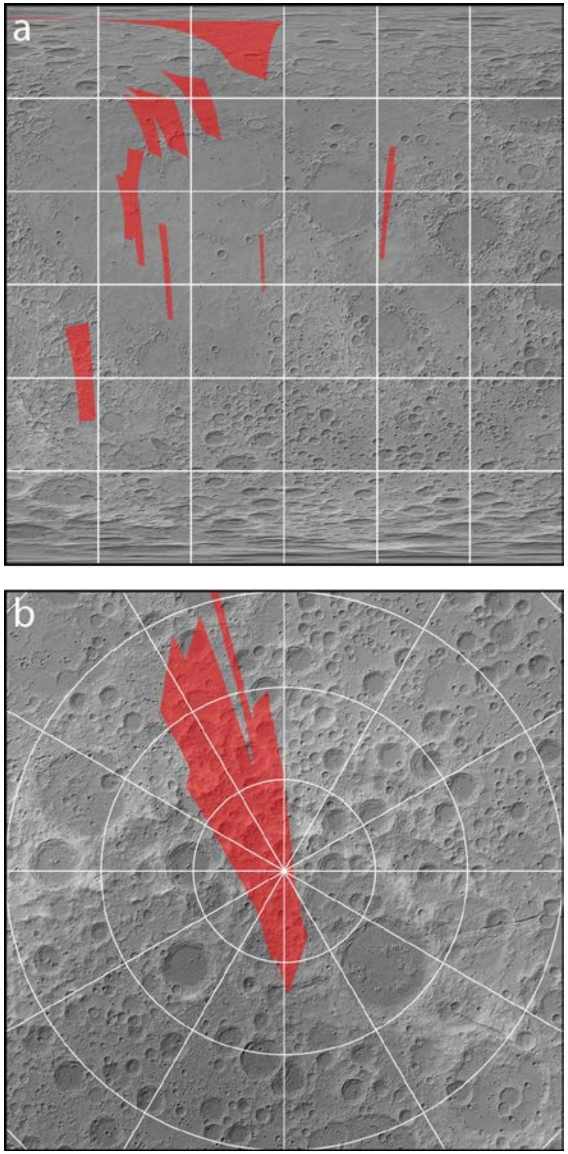
Introduction

- Mini-RF is a hybrid dual-polarized synthetic aperture radar (SAR) that operated in concert with the Arecibo Observatory (AO) to collect bistatic radar data of the lunar nearside from 2012 to 2015.

  - The purpose of this bistatic campaign was to observe the scattering characteristics of the upper meter(s) of the lunar regolith, as a function of the bistatic angle, and to search for a coherent backscatter opposition response indicative of the presence of water ice.

  - A variety of lunar terrain types were sampled over a range of incidence and bistatic angles; including mare, highland, pyroclastic, crater ejecta, and crater floor materials.



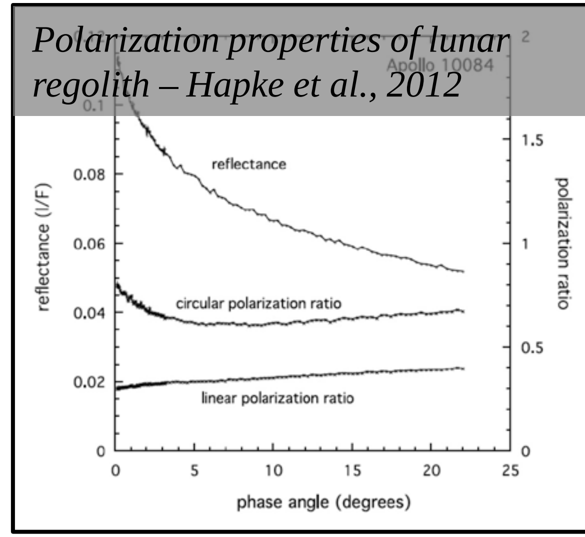
INTRODUCTION

Observation	Date		Time (GMT)		Location		PRI (μs)	Imaging Geometry			
	Year	DOY	Start	Stop	Latitude (°)	Longitude (°)		Incidence (°)	Emission (°)	Bistatic angle (°)	Range (km)
Hansteen[1]	2011	096	17:33:26	17:39:32	-2 to -15	-52 to -53	640	47 to 49	33 to 59	0.1 to 15	50 to 79
Newton	2012	137	13:38:20	13:46:20	-71 to -90	-180 to 180	625	66 to 89	72 to 81	6 to 18	108 to 195
La Condamine S	2012	220	07:51:18	07:57:43	47 to 67	-22 to -31	525	57 to 76	53 to 62	0.1 to 20	251 to 334
Cabeus	2012	220	08:30:04	08:40:04	-82 to -90	-180 to 180	1600	79 to 93	73 to 90	0.1 to 21	104 to 344
Kepler	2012	276	05:35:20	05:38:45	1 to 12	-37 to -39	700	40 to 44	33 to 46	0.1 to 12	119 to 163
Aristarchus	2012	304	04:10:35	04:17:00	22 to 35	-49 to -54	625	55 to 64	49 to 64	0.1 to 12	187 to 290
Newton	2013	071	17:28:38	17:35:03	-71 to -90	-180 to 180	800	67 to 87	75 to 83	3 to 16	125 to 227
Harpalus	2013	073	18:08:40	18:15:05	41 to 61	-39 to -50	800	59 to 75	52 to 66	0.1 to 20	220 to 341
Kepler	2013	073	18:21:21	18:31:21	-12 to 20	-35 to -40	800	41 to 49	41 to 60	3 to 22	105 to 225
Bouguer	2013	127	14:29:21	14:35:46	41 to 61	-30 to -45	1300	56 to 75	58 to 77	0.1 to 18	248 to 466
Cabeus	2013	127	15:06:01	15:16:01	-67 to -90	-180 to 180	1300	67 to 92	69 to 87	0.1 to 30	85 to 275
Byrgius A	2013	157	13:53:26	13:59:51	-16 to -36	-61 to -66	1000	68 to 73	52 to 73	0.1 to 18	93 to 227
Byrgius A	2013	157	15:52:02	15:58:27	-16 to -36	-62 to -65	1000	68 to 73	49 to 67	4 to 22	87 to 180
La Condamine S	2013	181	10:21:01	10:27:26	47 to 67	-20 to -35	1400	57 to 76	61 to 76	0.1 to 16	271 to 460
Cabeus	2013	181	10:59:30	11:09:30	-67 to -90	-180 to 180	1750	66 to 96	73 to 90	0.1 to 24	110 to 427
Haworth	2013	235	06:56:10	07:02:35	-77 to -90	-180 to 180	1000	73 to 93	76 to 88	0.1 to 16	138 to 315
de Gerlache	2013	236	06:38:26	06:44:51	-79 to -90	-180 to 180	1100	78 to 98	77 to 89	1 to 20	130 to 334
Littrow D	2013	273	11:39:18	11:49:18	17 to 39	32 to 35	575	35 to 47	31 to 44	0.1 to 15	131 to 189
Littrow D	2013	273	13:37:44	13:47:44	8 to 39	31 to 36	990	33 to 48	36 to 54	1 to 21	126 to 222
Anaxagoras	2013	303	12:43:51	12:50:16	65 to 85	-3 to -36	1600	60 to 80	70 to 83	3 to 23	363 to 594
Cabeus[2]	2013	345	22:59:58	23:06:23	-74 to -84	-15 to -53	1500	74 to 85	66 to 88	1 to 29	70 to 281
Cabeus	2013	346	00:59:26	01:05:51	-72 to -90	-180 to 180	1500	73 to 92	65 to 86	0.1 to 28	68 to 237
Cabeus	2014	116	13:43:32	13:53:32	-63 to -90	-180 to 180	1150	62 to 92	73 to 88	0.1 to 25	132 to 373
Littrow D	2014	153	20:11:44	20:21:44	7 to 39	31 to 35	600	31 to 46	29 to 43	0.1 to 17	120 to 188
Byrgius A	2014	201	10:13:17	10:23:17	-12 to -44	-59 to -67	850	71 to 80	51 to 78	0.1 to 25	92 to 292
Aristarchus	2014	227	08:51:07	09:01:07	5 to 37	-44 to -52	1050	52 to 65	45 to 64	0.1 to 14	137 to 268
Byrgius A	2014	228	08:48:49	08:58:49	-13 to -45	-56 to -68	1150	72 to 79	61 to 87	2 to 14	114 to 455
Littrow D	2014	235	13:44:54	13:54:54	14 to 45	32 to 36	600	30 to 49	29 to 38	0.1 to 20	125 to 178

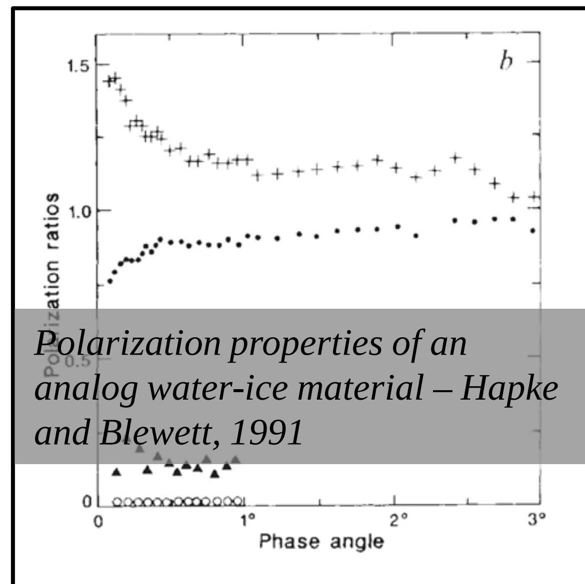
INTRODUCTION

<u>Coherent Backscatter Opposition Effect (COBE)</u>

- COBE results from the coherent addition of radar energy that travel the same path in opposite directions between multiple scatterers in a medium.
  - Produces an opposition peak, i.e., a peak centered at zero phase [Hapke, 1990]
- Experimental work at optical wavelengths has demonstrated that water ice and lunar regolith can produce an opposition response [Hapke and Blewett, 1991; Hapke et al., 1998; Nelson et al., 2000, 2002; Piatek et al., 2004].
  - A relatively narrow opposition response, involving phase angles ≤ ~1°, is observed for simulated water ice [Hapke and Blewett, 1991].
  - A broader opposition response, involving phase angles ≤ ~5°, is observed for lunar regolith [Hapke et al., 1998; Hapke et al., 2012].



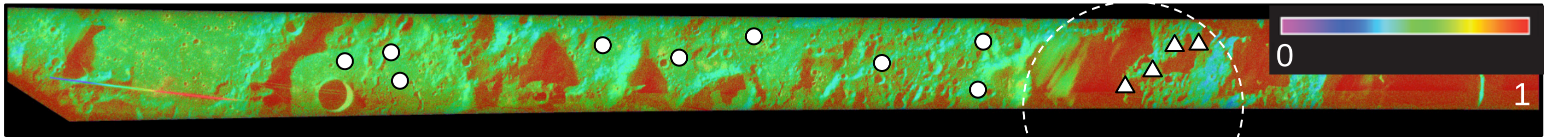
Polarization properties of lunar regolith – Hapke et al., 2012

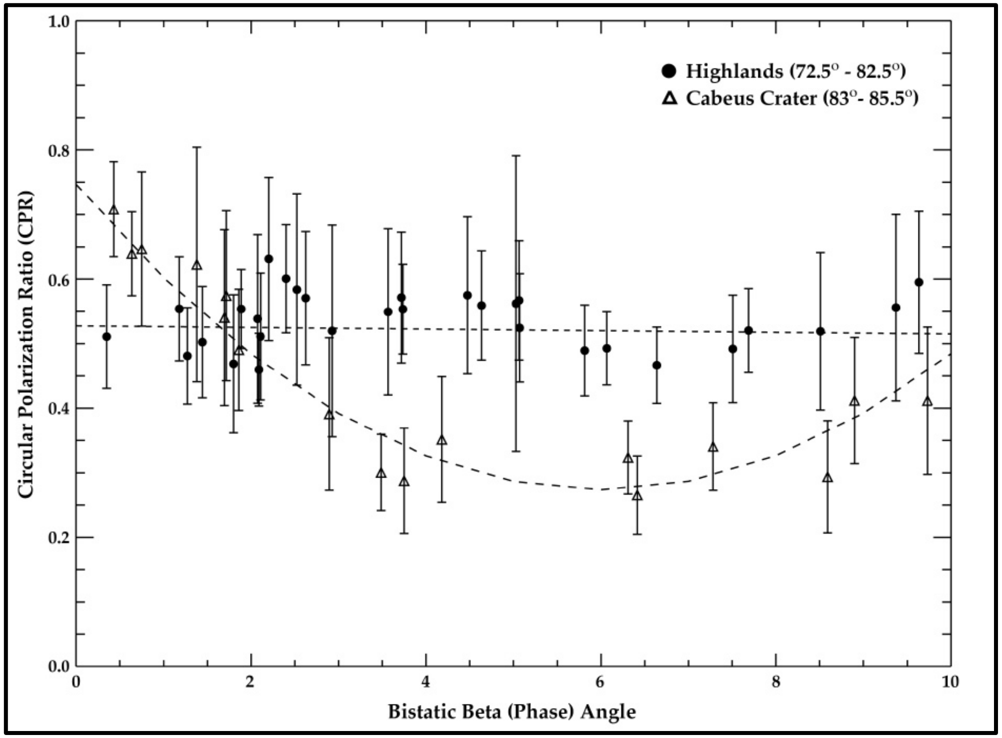


Polarization properties of an analog water-ice material – Hapke and Blewett, 1991

Initial results: Cabeus

Observation – 2013-127 (May 7)

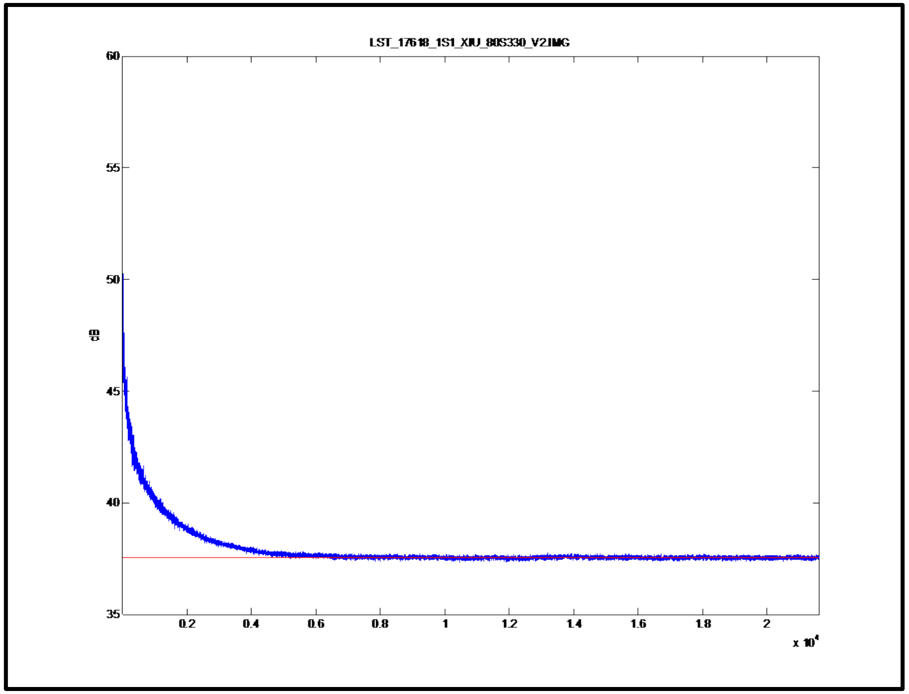


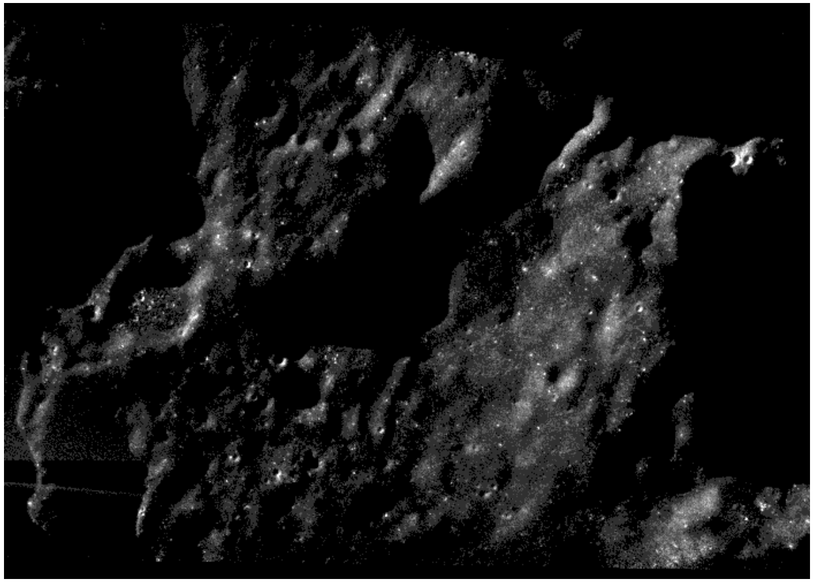


- Cabeus is a 98 km dia. pre-Nectarian crater (84.9°S, 35.5°W)
  - The CPR of highland terrains equatorward of Cabeus crater are relatively uniform over bistatic angles <10°.
  - The CPR of the floor/wall of Cabeus crater is variable as a function of bistatic angle

NOISE FILTERING

OBSERVATION – 2013-127 (MAY 7)





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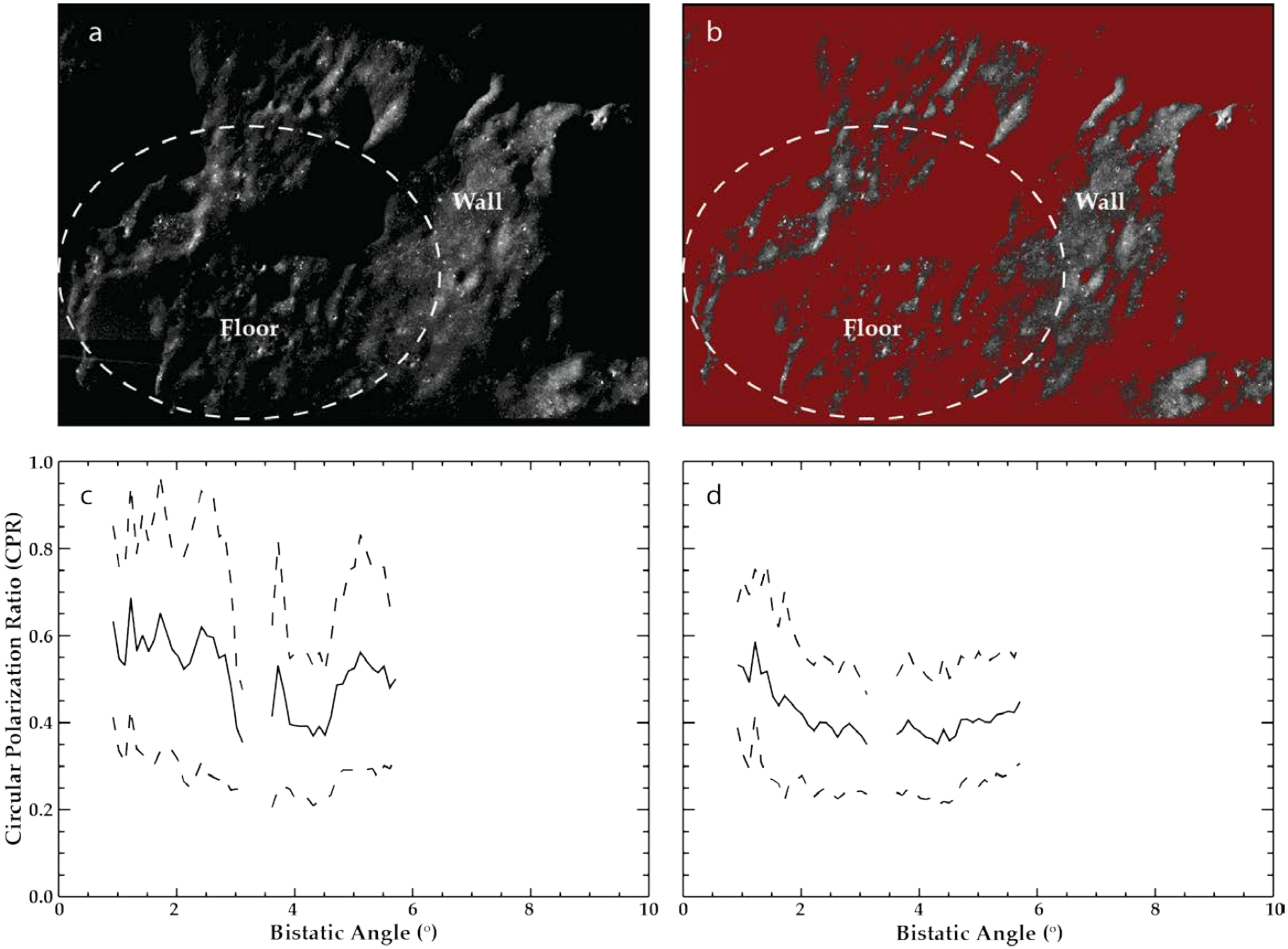

NEW RESULTS: CABEUS

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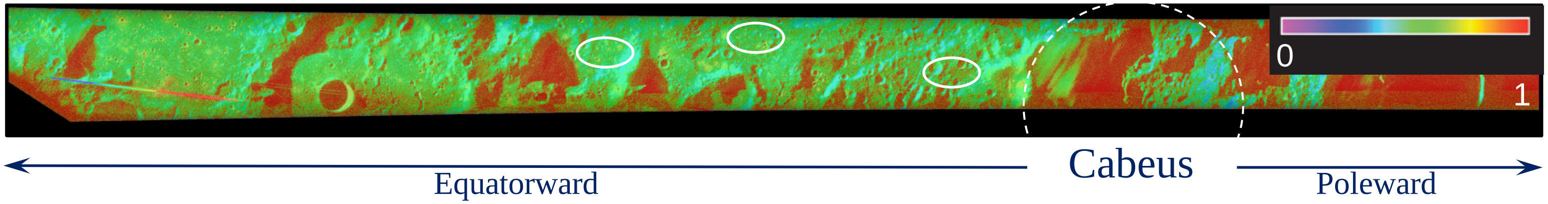

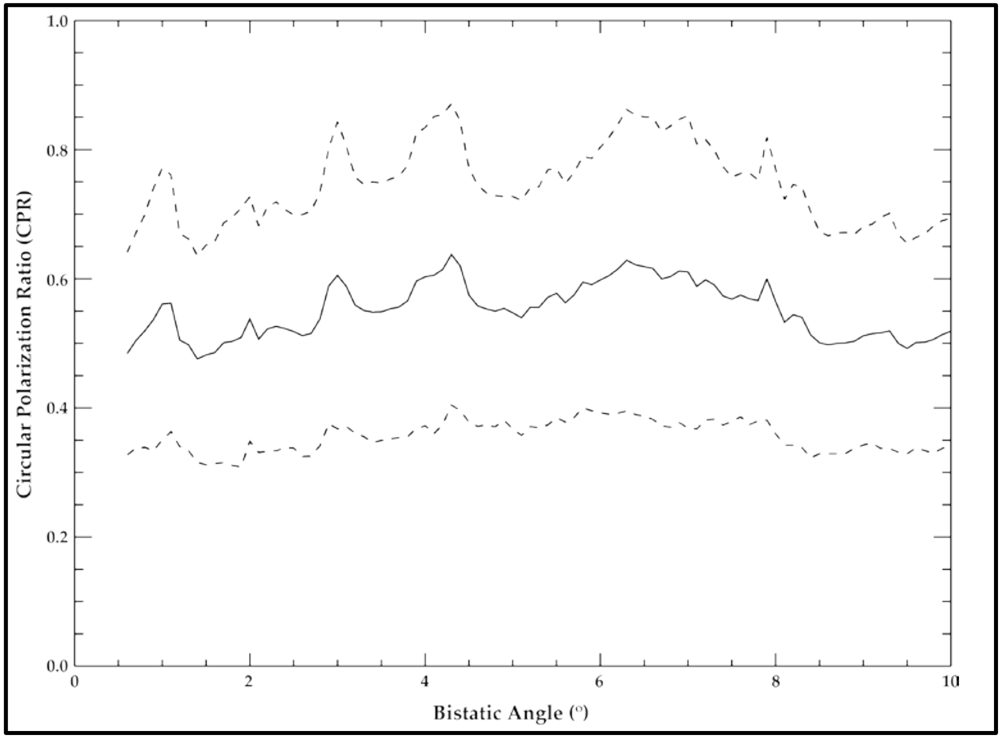

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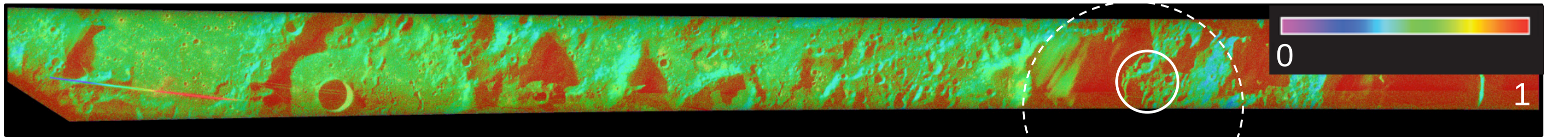
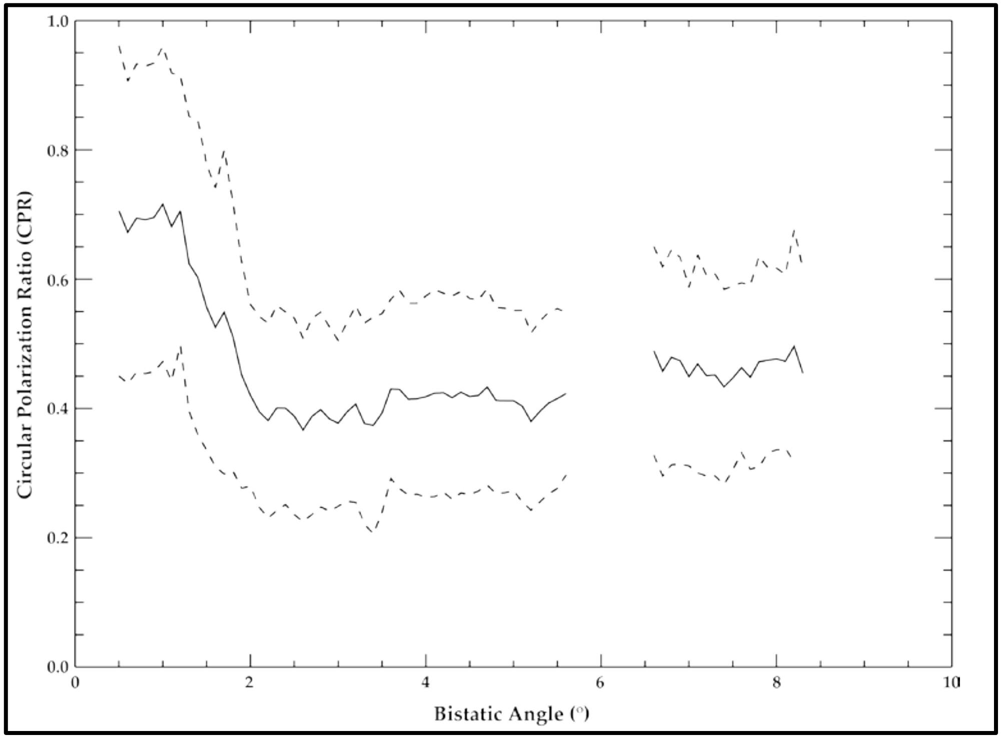


Equatorward — Cabeus — Poleward



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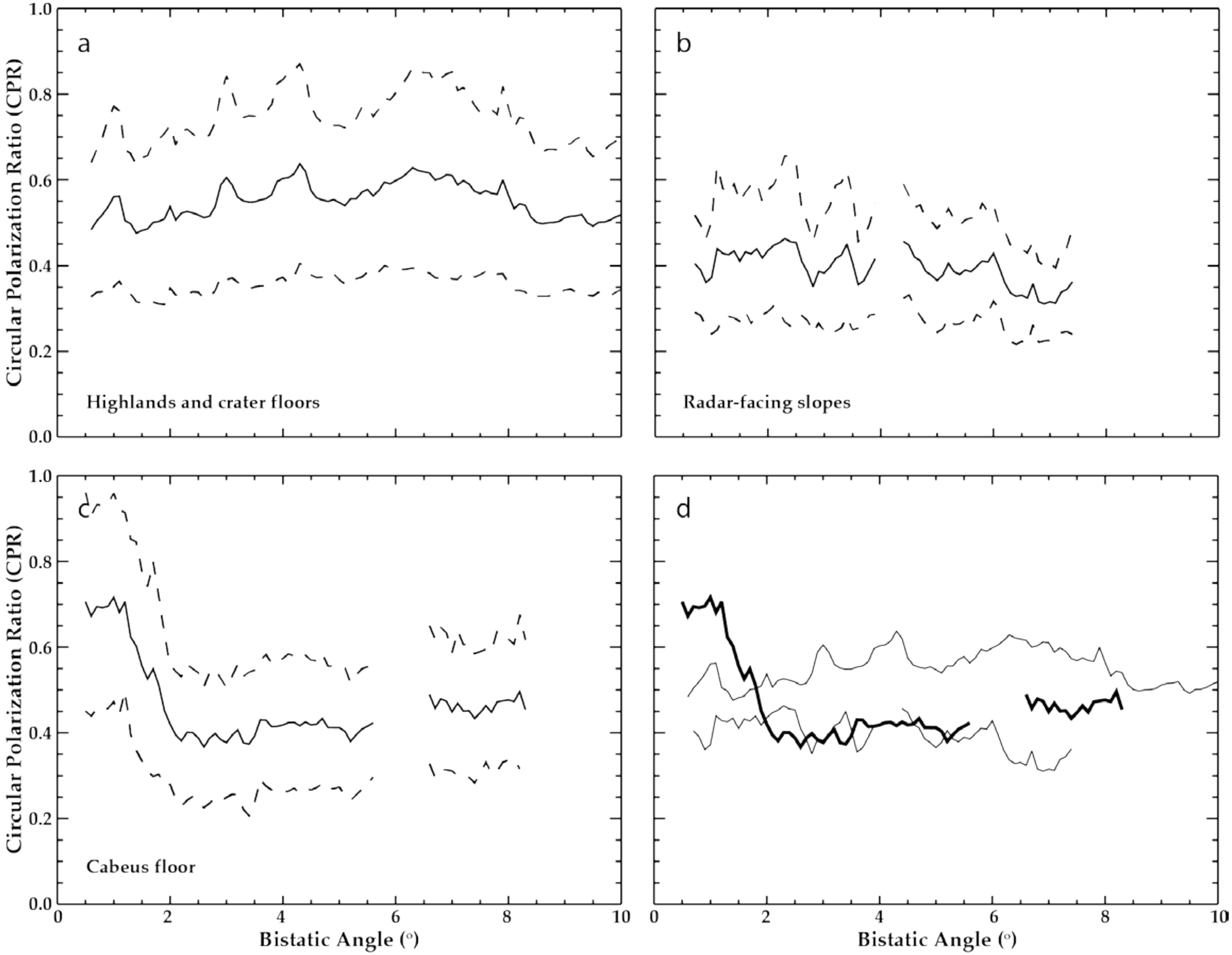
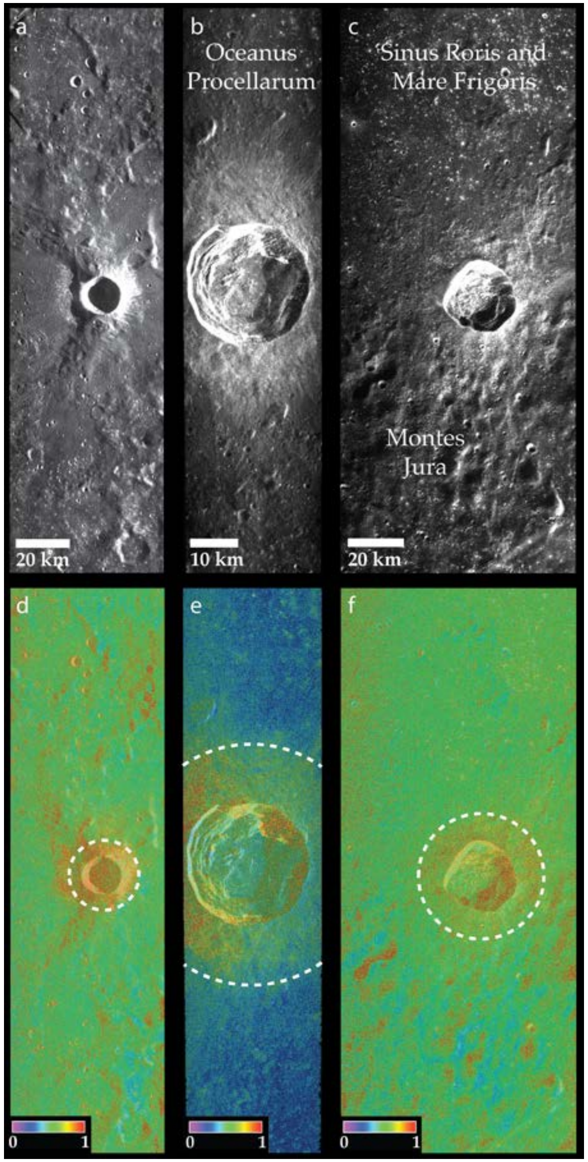
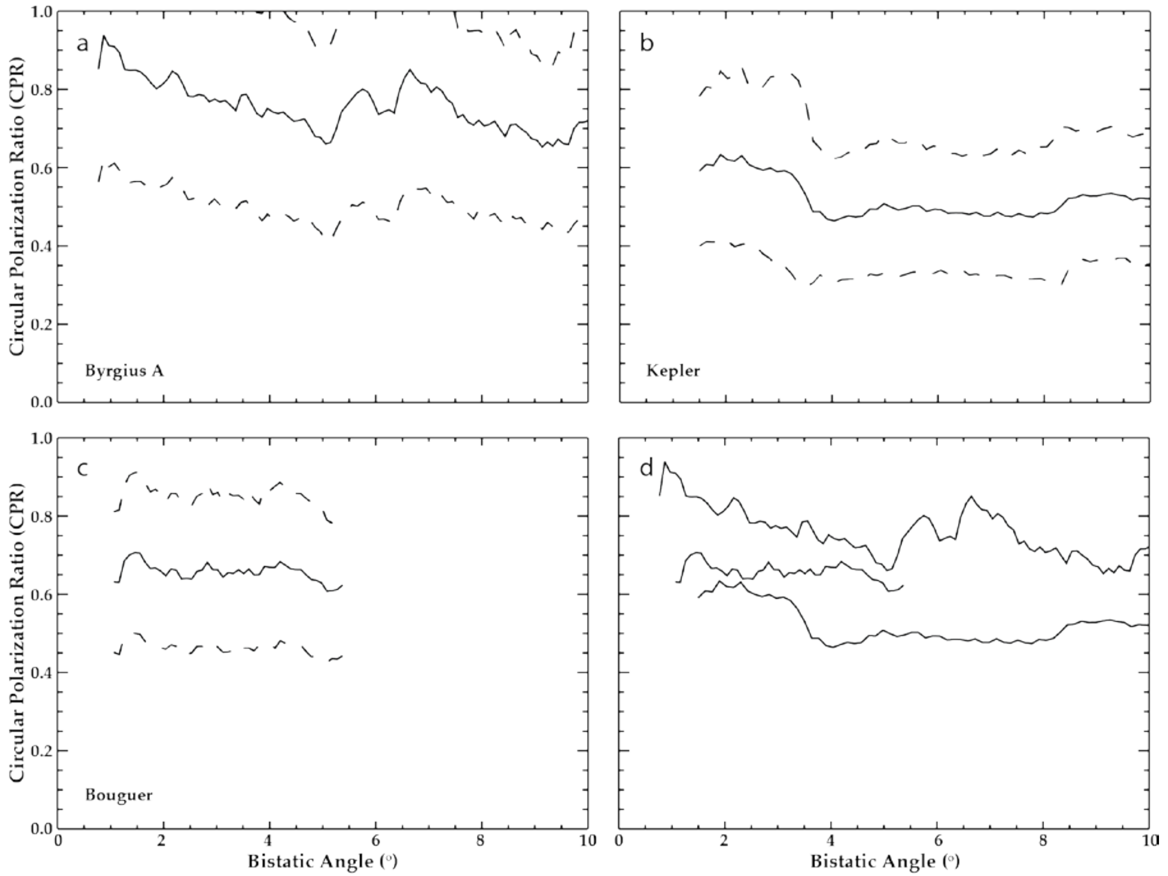
  - The CPR of highland terrains equatorward of Cabeus crater are relatively uniform over bistatic angles <10°.
  - The CPR of the floor/wall of Cabeus crater is variable as a function of bistatic angle
    - Plot includes 60,000 measurements spanning 5 observations.

RESULTS: COMPARISON

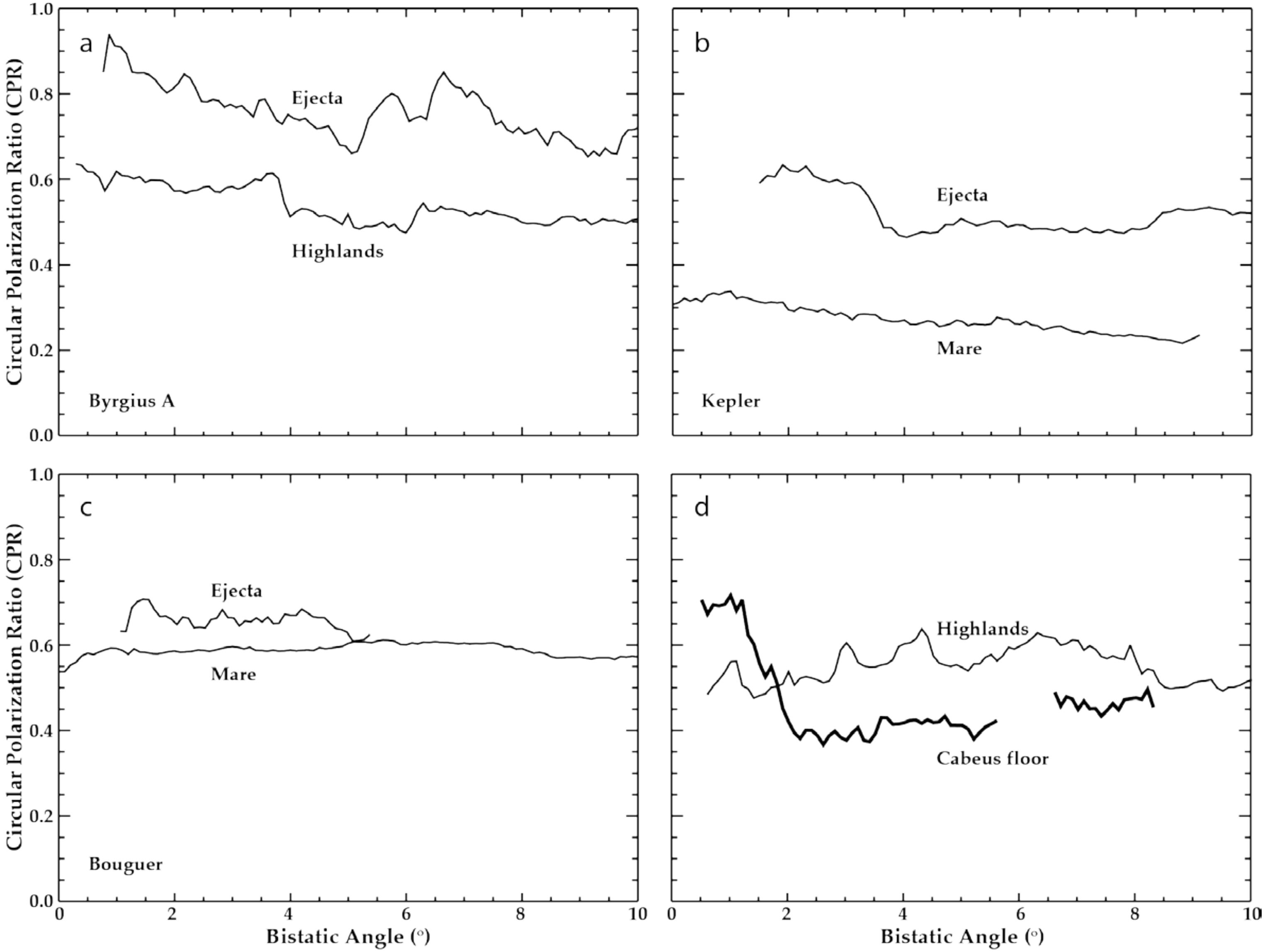


RESULTS: CRATER EJECTA





Results: Comparison



RESULTS: EUREKA!?!?

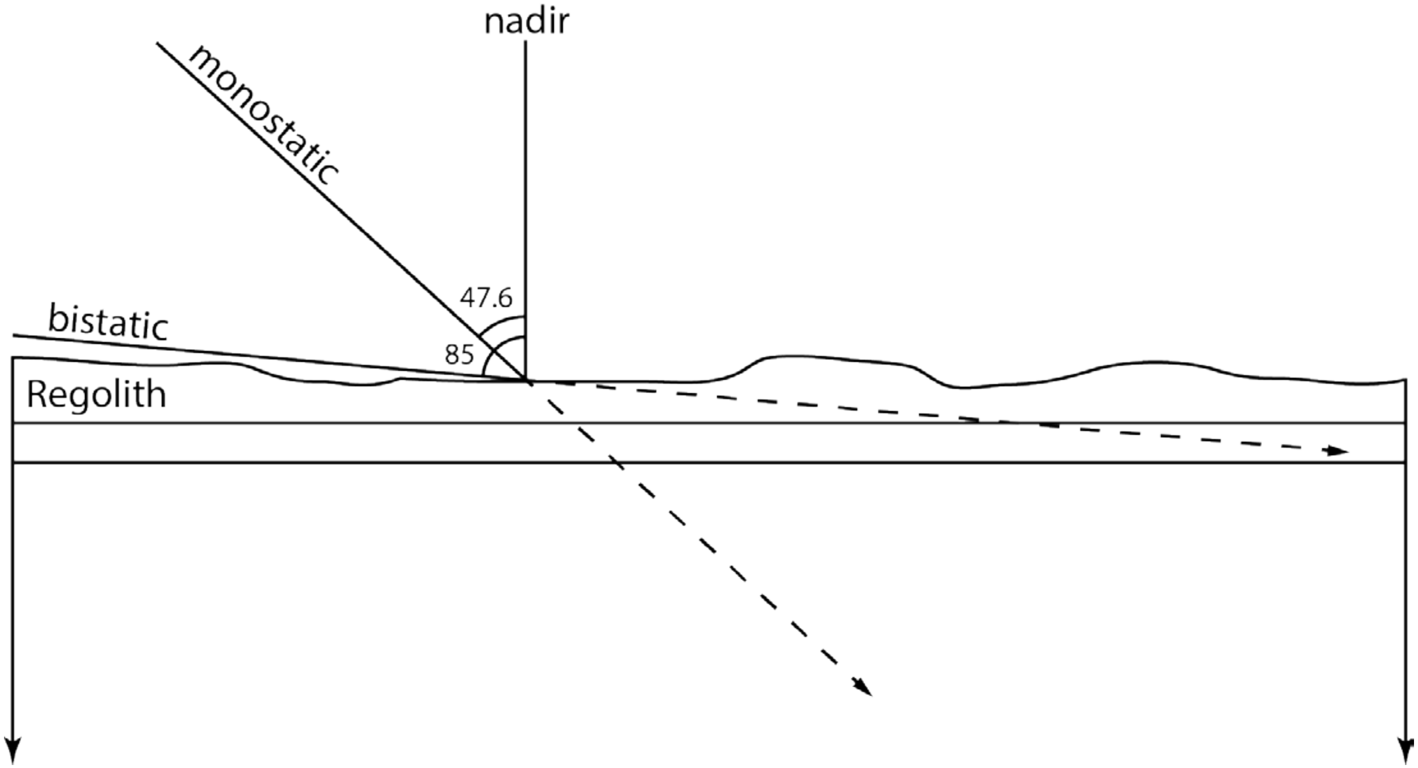
Water ice at Cabeus?

- The measured opposition response of the imaged portion of Cabeus's floor is narrow and strong, indicative of a COBE.
- The response is not observed in association with permanently shadowed regions of Cabeus but it is in a region where water ice can be stable within the top meter of the surface [Paige et al., 2010].
- The character of the response is unique with respect to all other lunar terrains observed during the Mini-RF bistatic campaign.
- However, a key issue with water ice as the explanation for the opposition response of Cabeus floor materials is the measured CPR of the deposit for bistatic angles $< 0.5°$.
  - These data were gathered by Mini-RF monostatic [Neish et al., 2011] and ground-based [e.g., Campbell et al., 2006] observations of the crater
  - They are not consistent with CPR measurements at similar bistatic angles for other known icy materials [e.g,, Ostro et al., 1992; Harmon et al., 1994; Black et al., 2001].

RESULTS: EUREKA!?!?

Water ice at Cabeus?

- If water ice were present at the floor of Cabeus and it was concentrated in a relatively thin layer near the surface, it could explain the difference in the measured CPR of the terrain for Mini-RF monostatic versus bistatic observations.



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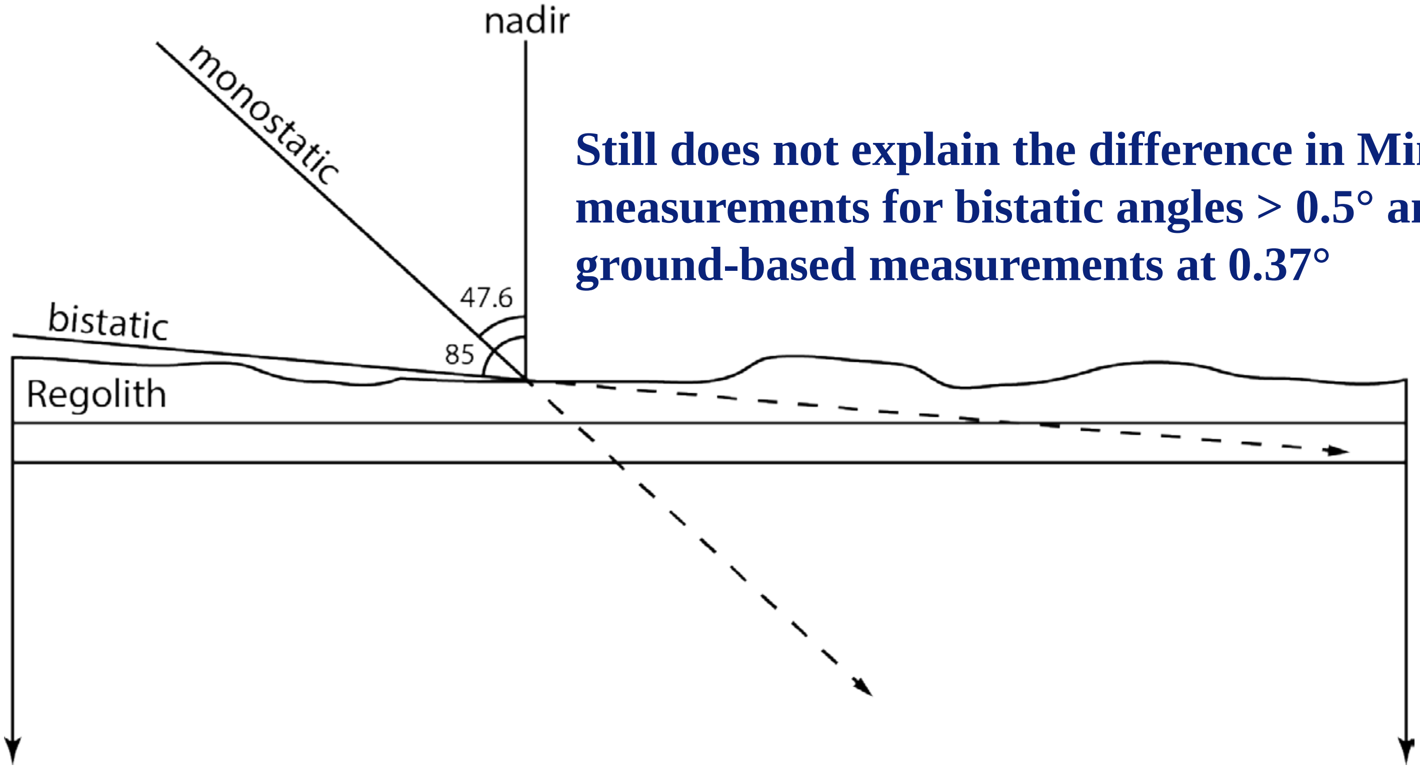
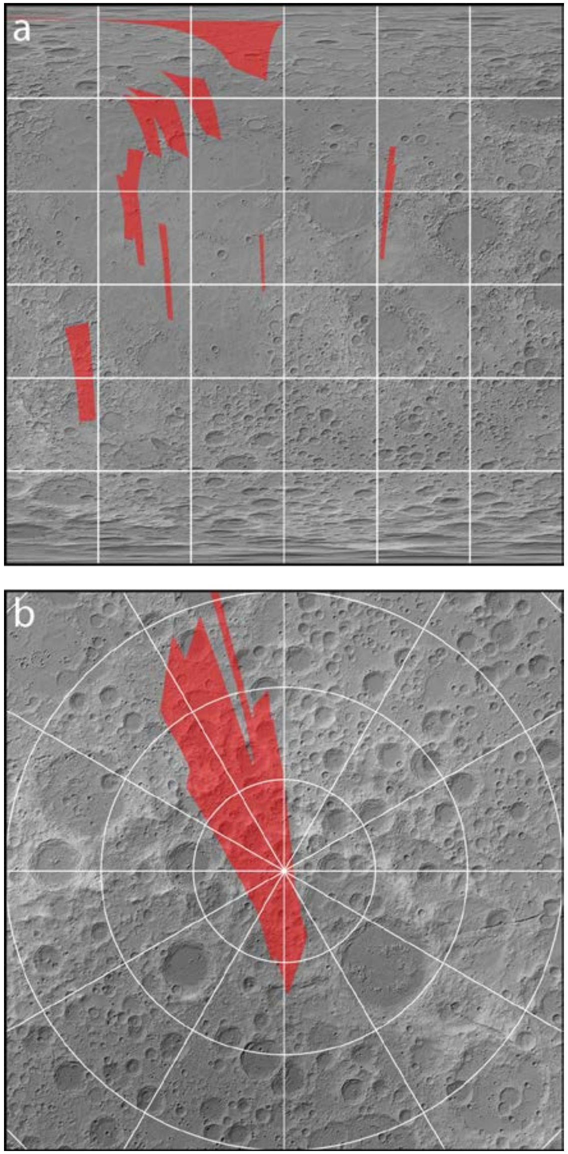


Still does not explain the difference in Mini-RF measurements for bistatic angles > 0.5° and ground-based measurements at 0.37°

Summary

- Mini-RF/AO S-band radar measurements of CPR as a function of bistatic angle indicate the presence of an opposition response for the ejecta of the Copernican-aged craters Byrgius A and Kepler and the floor of the south-polar crater Cabeus.
  - The responses of ejecta material varied by crater in a manner that suggests a relationship with crater age.
  - The character of the response for the floor of Cabeus differs from that of crater ejecta and appears unique with respect to all other lunar terrains observed.
    - Analysis of data for this region suggests that the unique nature of the response may indicate the presence of near surface deposits of water ice.



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