Simulation of Brightness Temperatures for the Microwave Radiometer (MWR) on the Aquarius/SAC-D Mission

Salman S. Khan

M.S. Defense

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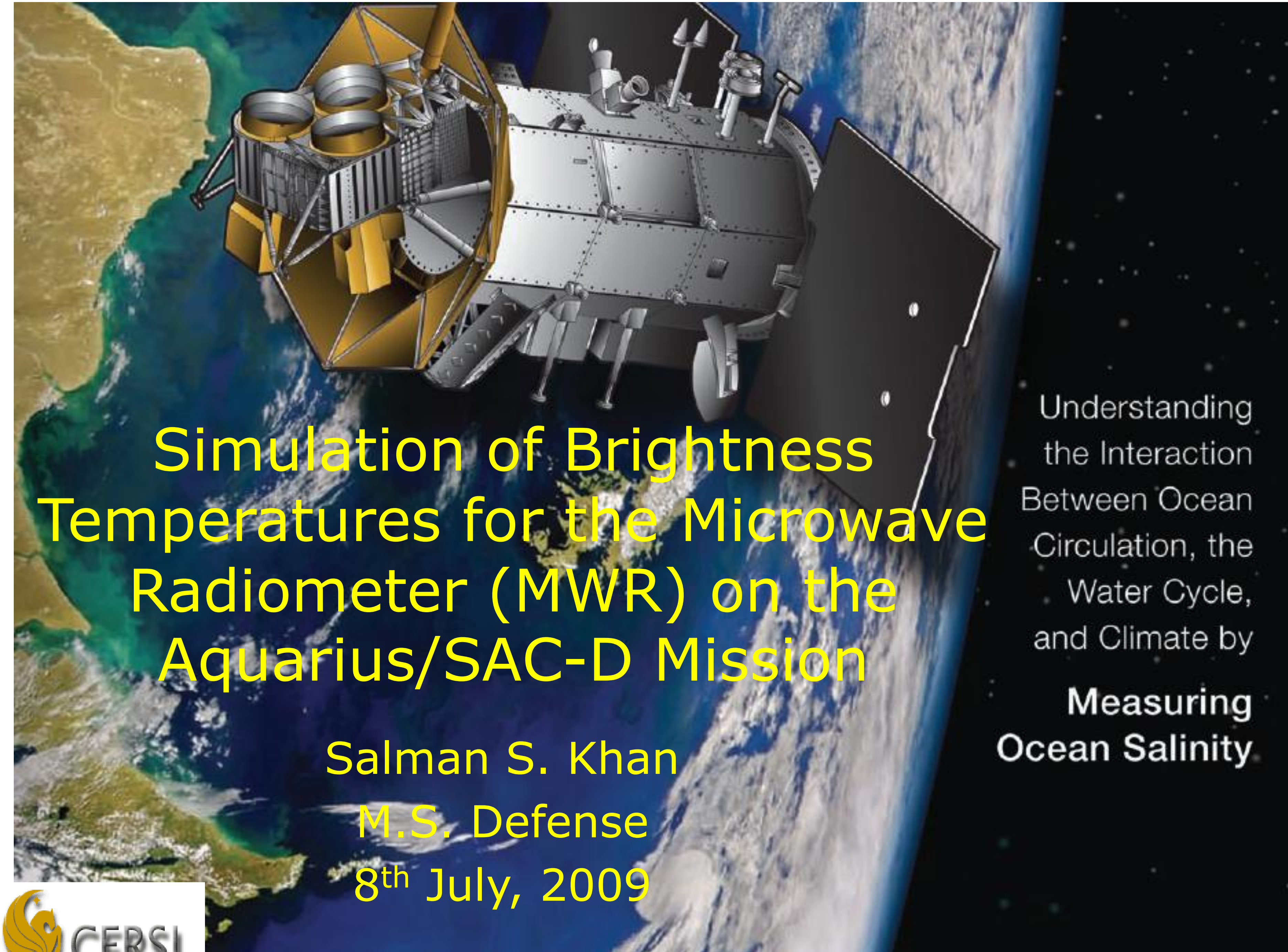


CFRSL

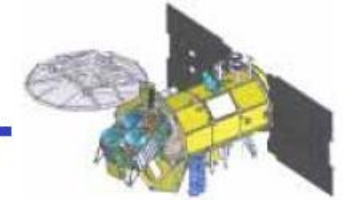
Outline

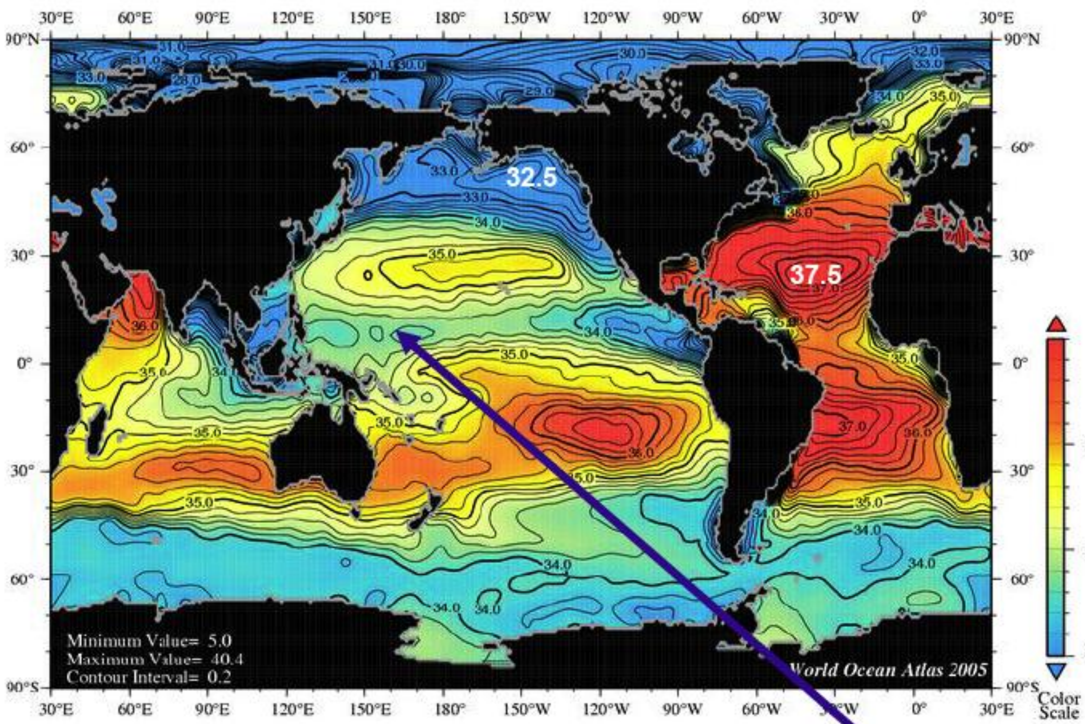
- Thesis Objective
- Aquarius Salinity Measurements
- Aquarius Radiometer/Scatterometer
- Microwave Radiometer (MWR)
- MWR T_b Simulation Requirements
- Yaw Steering Analysis
- Post-Launch Inter-Satellite Radiometric Calibration using WindSat

Thesis Objective

- Simulate realistic ocean brightness temperatures (T_b) for the 3-channel Microwave Radiometer (MWR) on Aquarius/SAC-D
  - To be used by CONAE for pre-launch geophysical retrieval algorithms development
- Evaluate the proposed MWR measurement geometry and verify the requirements for spatial/temporal sampling
- Perform a preliminary study for the post-launch inter-satellite radiometric calibration using the WindSat radiometer as a reference

AQUARIUS/SAC-D Dynamic Range and Accuracy





Mean Ocean SSS Dynamic Range is ~5 psu (32.5 to 37.5 open ocean)

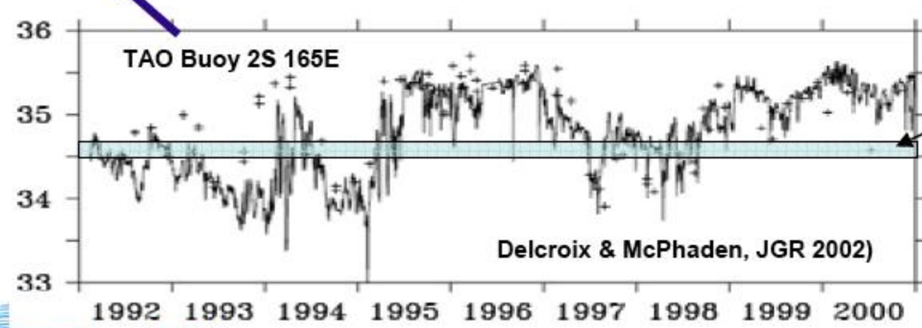
0.2 psu accuracy yields ~25:1 signal/error relative to mean field

Accuracy and signal/error improves with averaging interval (Table)

Random Error Reduction with Averaging Interval						
	Instantaneous	7 Days	28 Days	90 Days	1 Year	3 Years
Global RMS (psu)	0.87	0.33	0.20	0.09	0.05	0.03
Mean Signal/Error	6	15	25	55	110	190

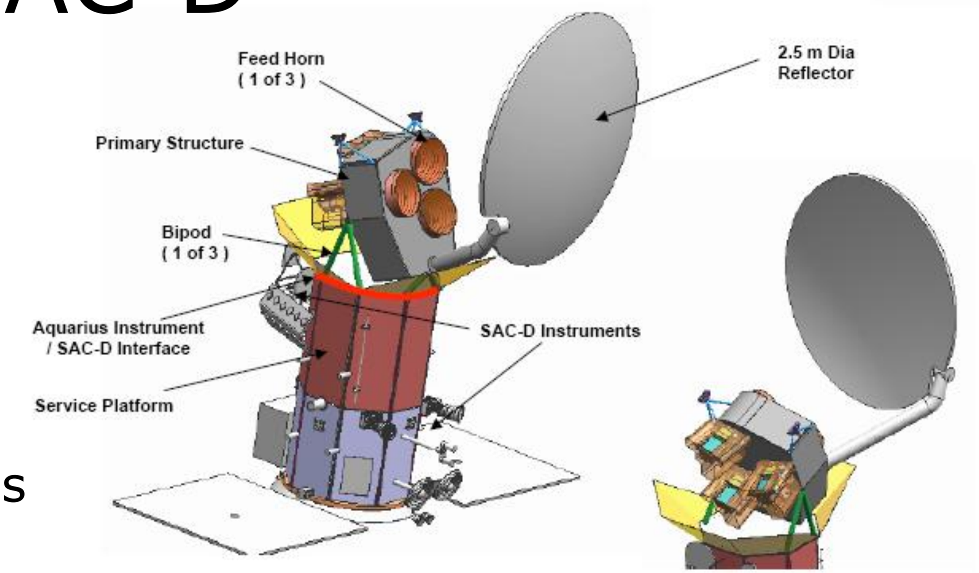
- Interannual SSS variability range is ~2 psu in the western tropical Pacific
- 0.2 psu monthly accuracy is at the detection limit of short time scales, and easily resolves the interannual signals related to El Niño

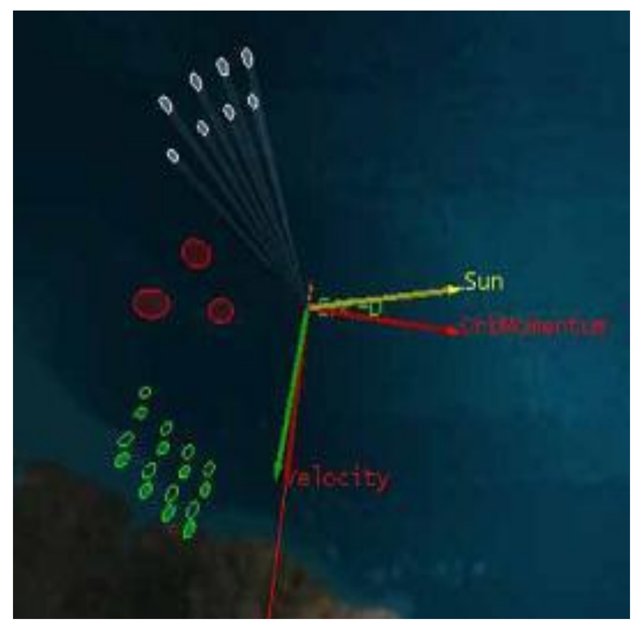
- Climatology maps based on the available historical data are interpolated over ~1000 km scales due to data sparseness.
- Aquarius' 150 km resolution will provide almost an order of magnitude improvement



Aquarius Radiometer/Scatterometer on SAC-D

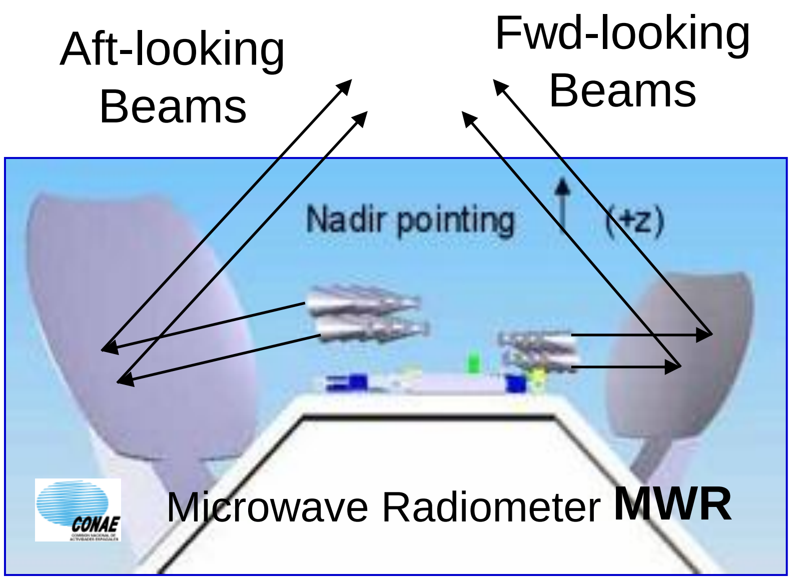
- Antenna
  - Radiometer & Scatterometer share feeds and 2.5 m reflector
  - Three footprints in pushbroom configuration
- Radiometer
  - 1.413 GHz V, H-pol & 3rd Stokes
- Scatterometer
  - 1.26 GHz H-pol
  - Provides a critical correction for surface roughness
- Beams
  - Inner – 76 x 94 Km
  - Middle – 84 x 120 Km
  - Outer – 96 x 156 Km



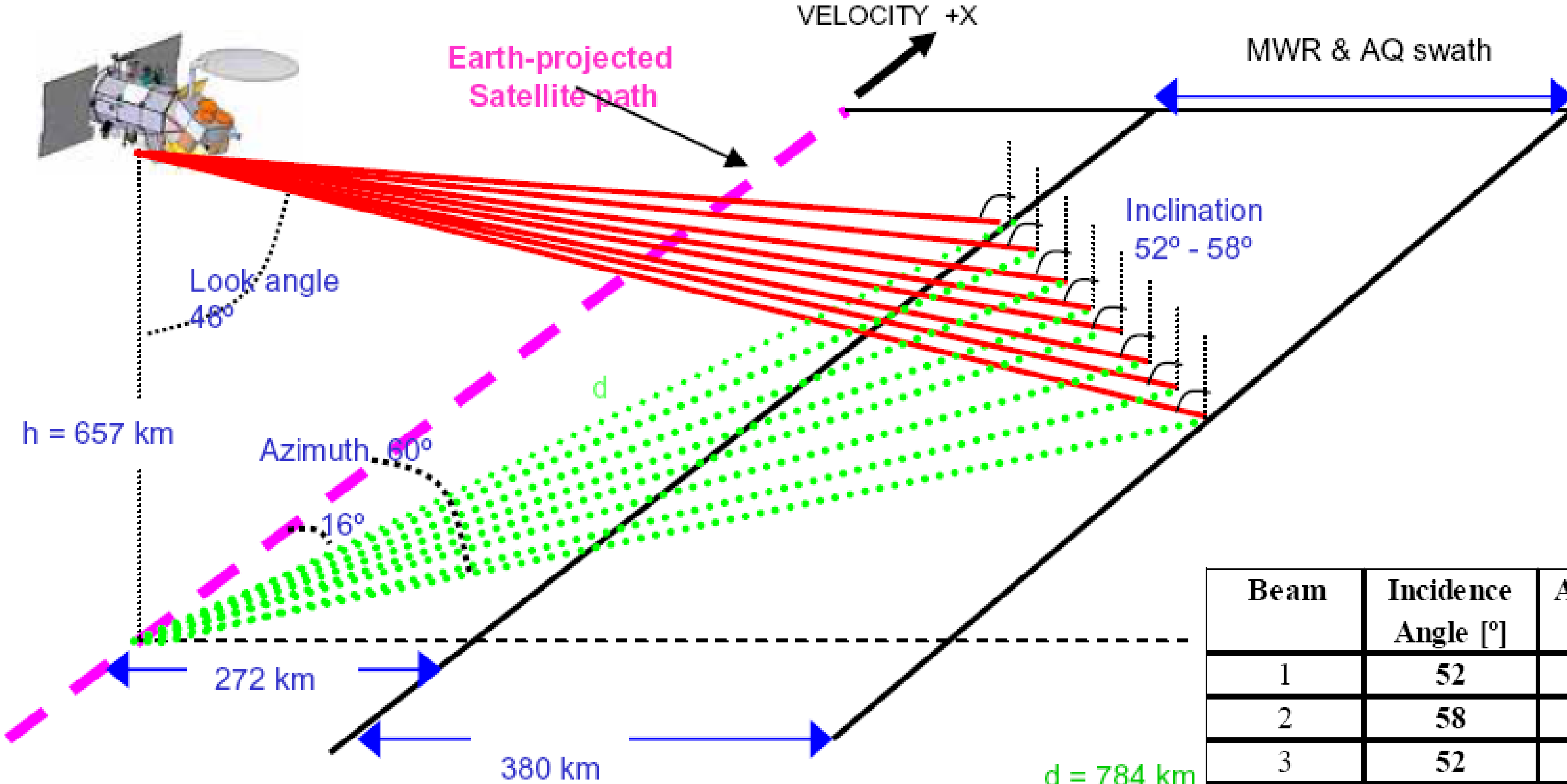


Microwave Radiometer (MWR) on SAC-D

- Radiometer
  - Two radiometers
    - 23.8 GHz (K band, V-pol)
    - 36.5 GHz (Ka band, H, V-pol, $+45^o$ & -45^o polarized output)
    - All the polarizations are measured simultaneously
- Antenna
  - Two Multi-beam parabolic-torus reflectors
    - Forward & Aft looking beams
    - 8 beams in push-broom configuration
    - Two incidence angles, 52^o & 58^o
    - IFOV Resolution of ~ 40 km



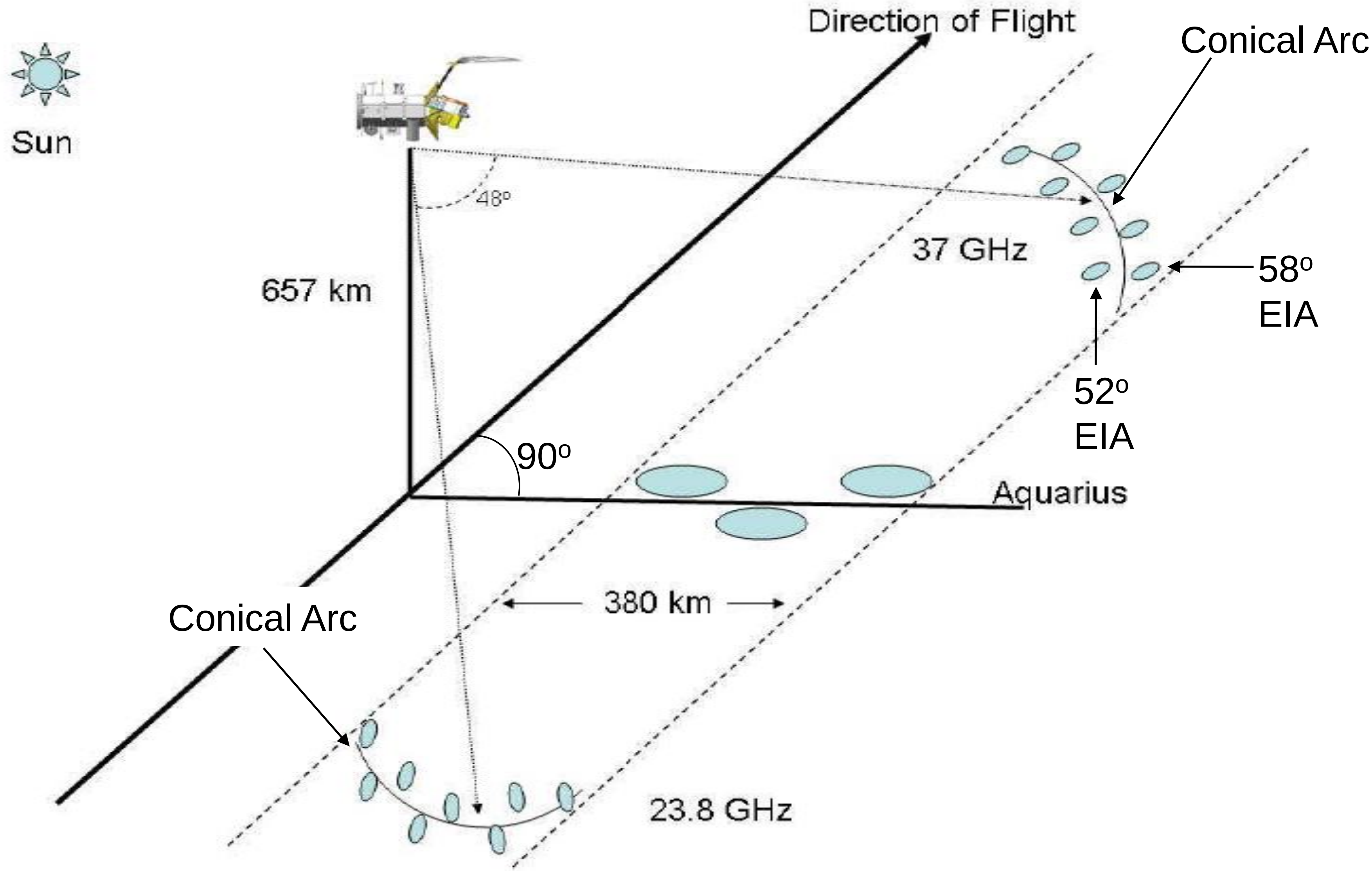
MWR Forward Beam (Ka-Band) Geometry



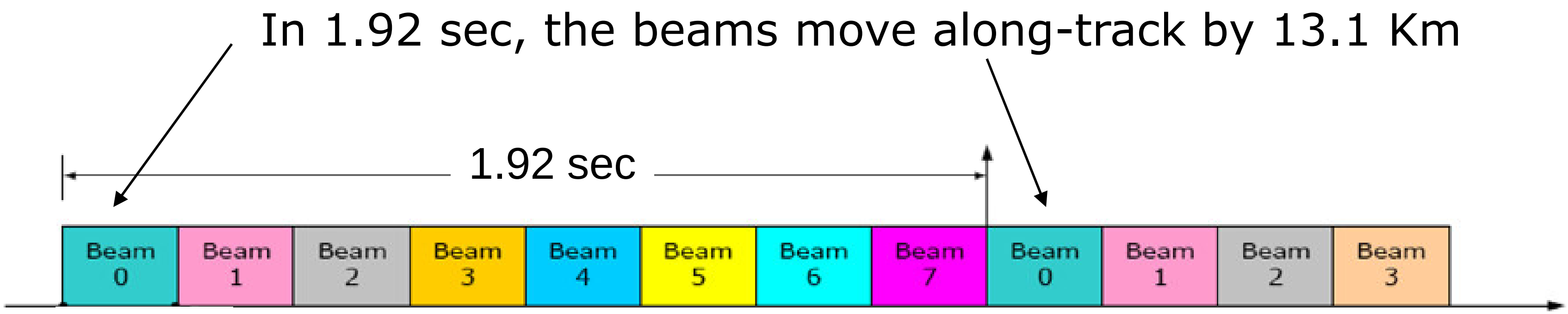
Beam	Incidence Angle [º]	Azimut [º]
1	52	24,56
2	58	23,16
3	52	32,33
4	58	29,56
5	52	41,44
6	58	37,12
7	52	52,97
8	58	46,13

- Satellite's velocity along +X
- Only forward beams are shown
- Four beams @ 52º & four @ 58º EIA, alternating

MWR Fwd & Aft Beam Geometry



MWR beams are sequentially sampled in time

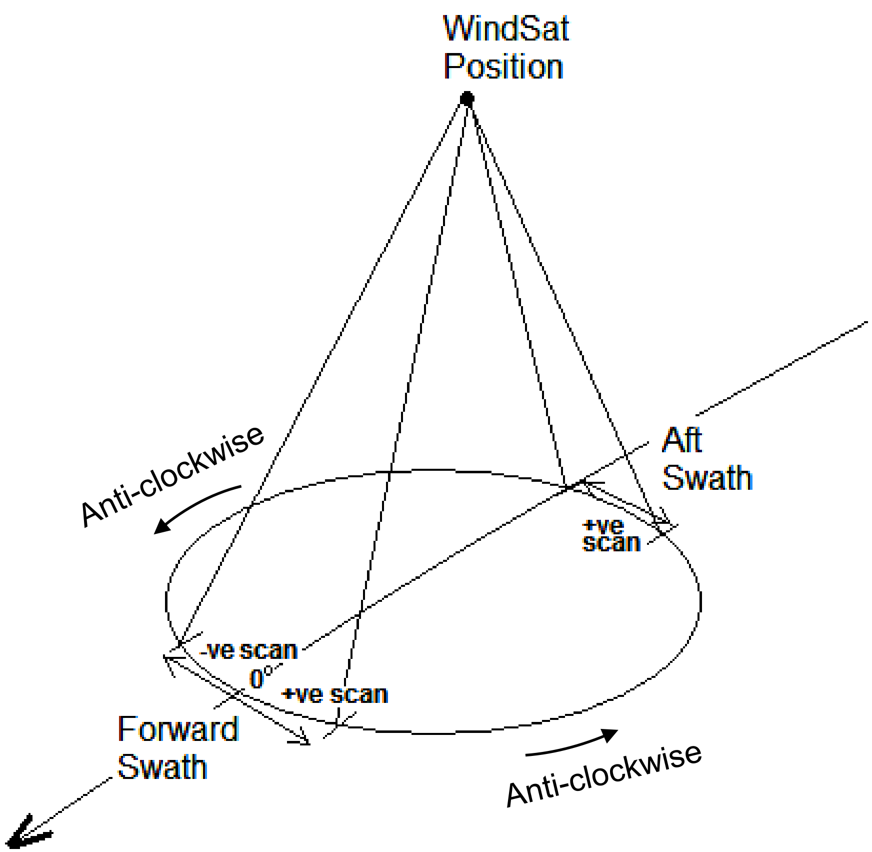


- The sampling time made the simulation very challenging since the beams are sampled sequentially at 0.24 sec intervals in which the spacecraft (and hence the footprint) moves as well

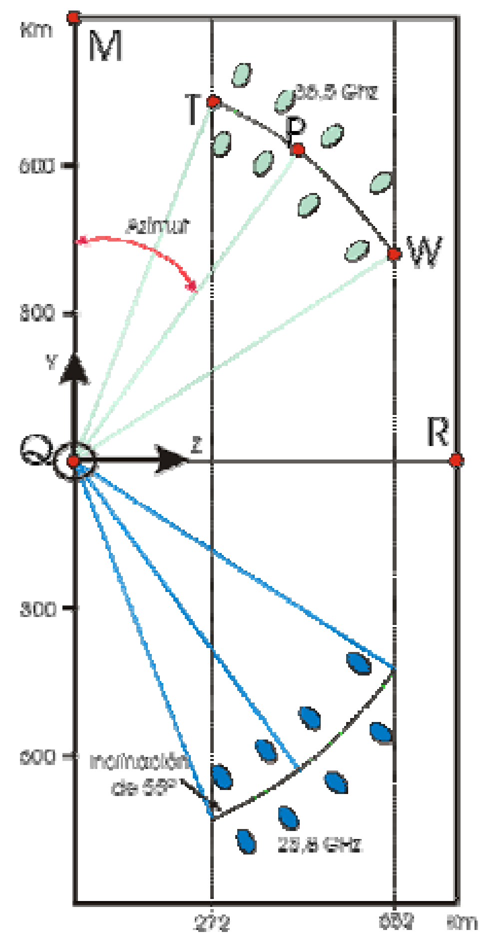
MWR T_b Simulation Requirements

WindSat & MWR Sensor Geometry

Why WindSat?
•Similar sun-synchronous orbits
•Similar frequency channels
•High resolution WindSat IDR

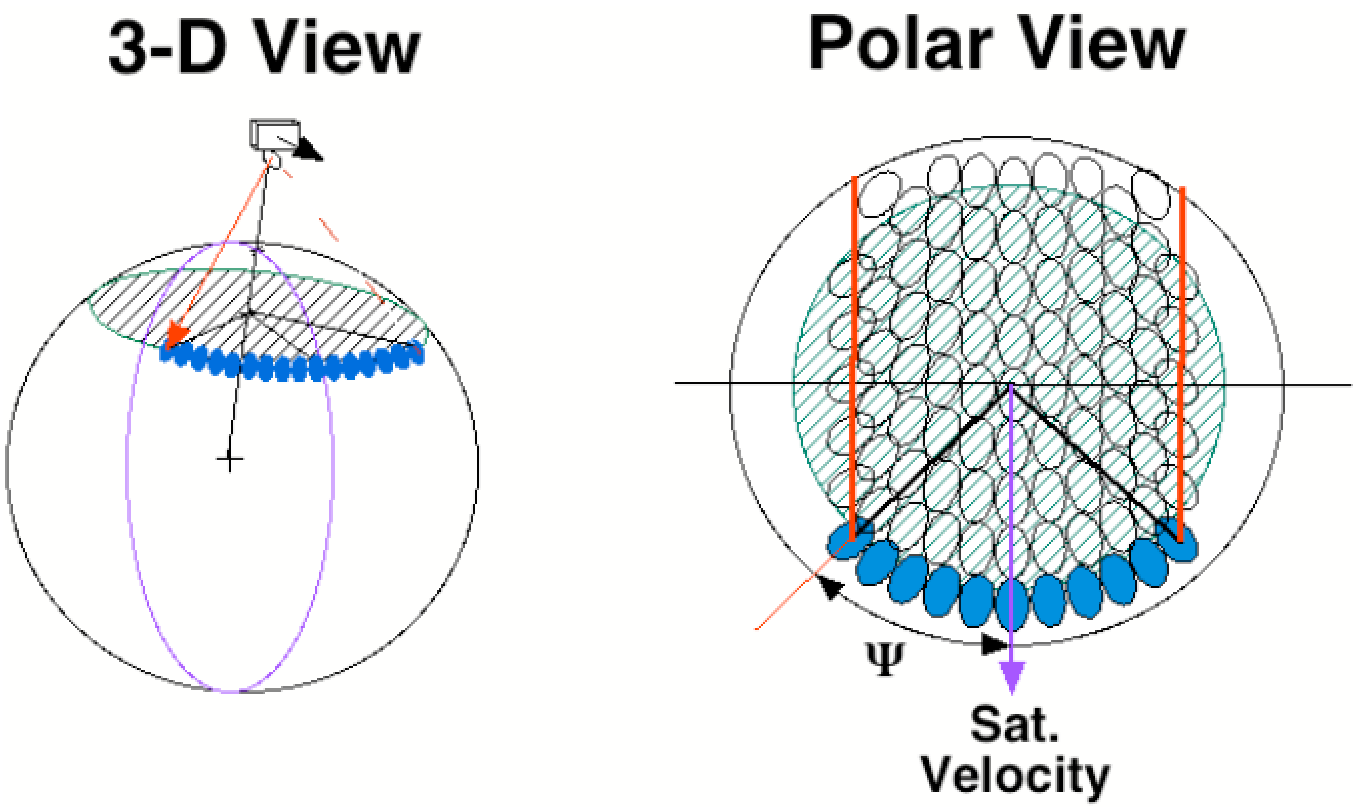


WindSat Conical Scanning Radiometer



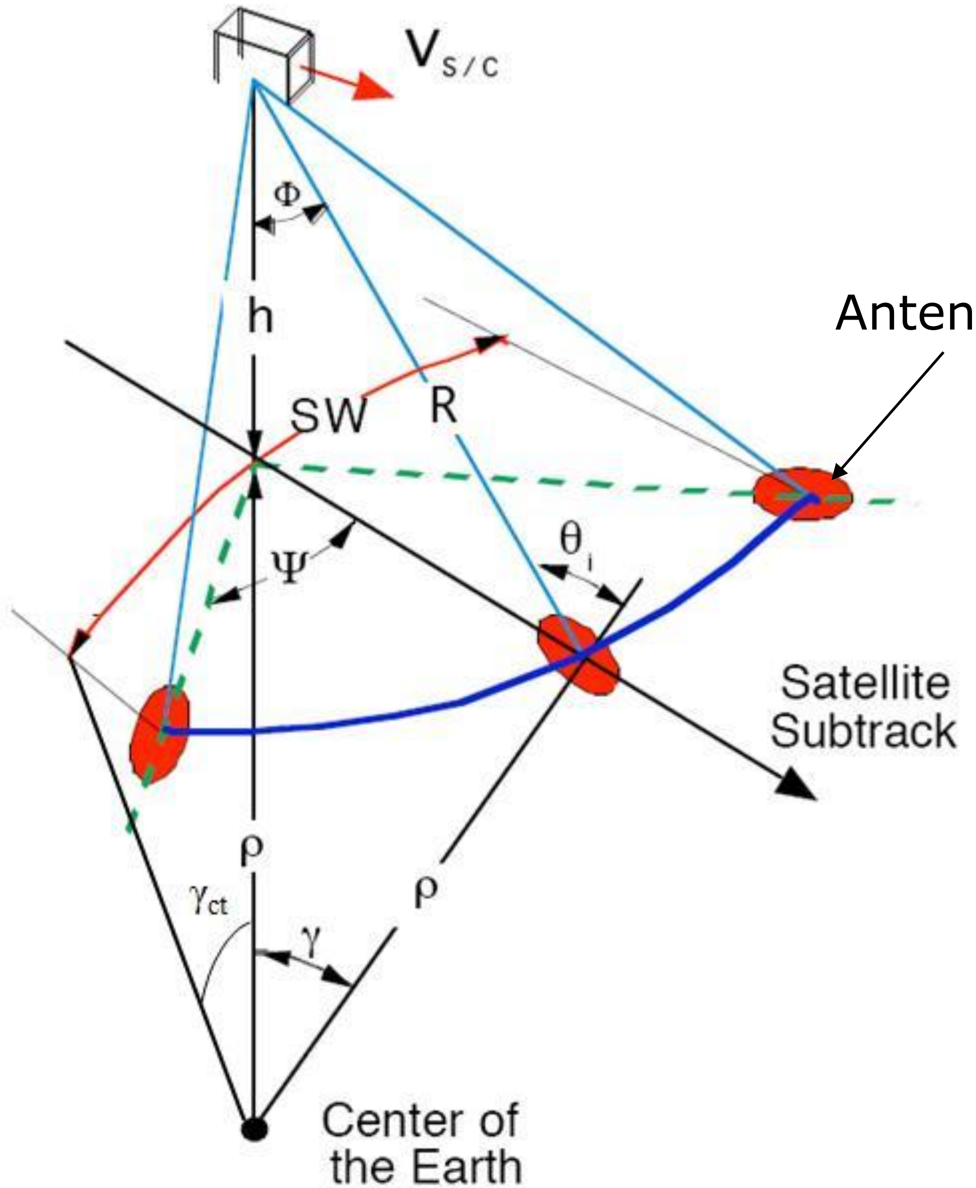
MWR Pushbroom Radiometer

Conical Scanning Sensor Geometry



Note: Partial conical scan over ± Ψ° azimuth

Conical Scanning Sensor Geometry cont.1



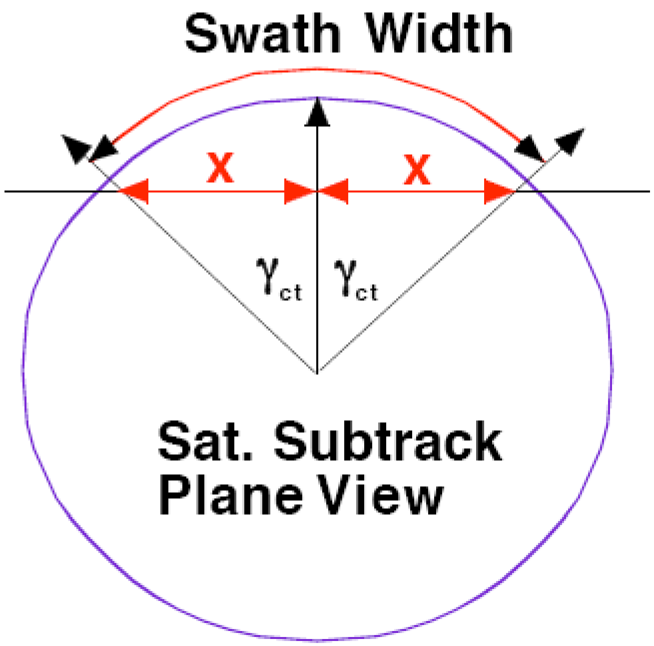
MWR Swath Width

Cross-Track Plane

$$\sin(\gamma_{ct}) = \sin(\gamma) * \sin(\Psi)$$

$$\gamma_{ct} = \sin^{-1}\{\sin(\gamma) * \sin(\Psi)\}$$

where γ is measured in incident plane



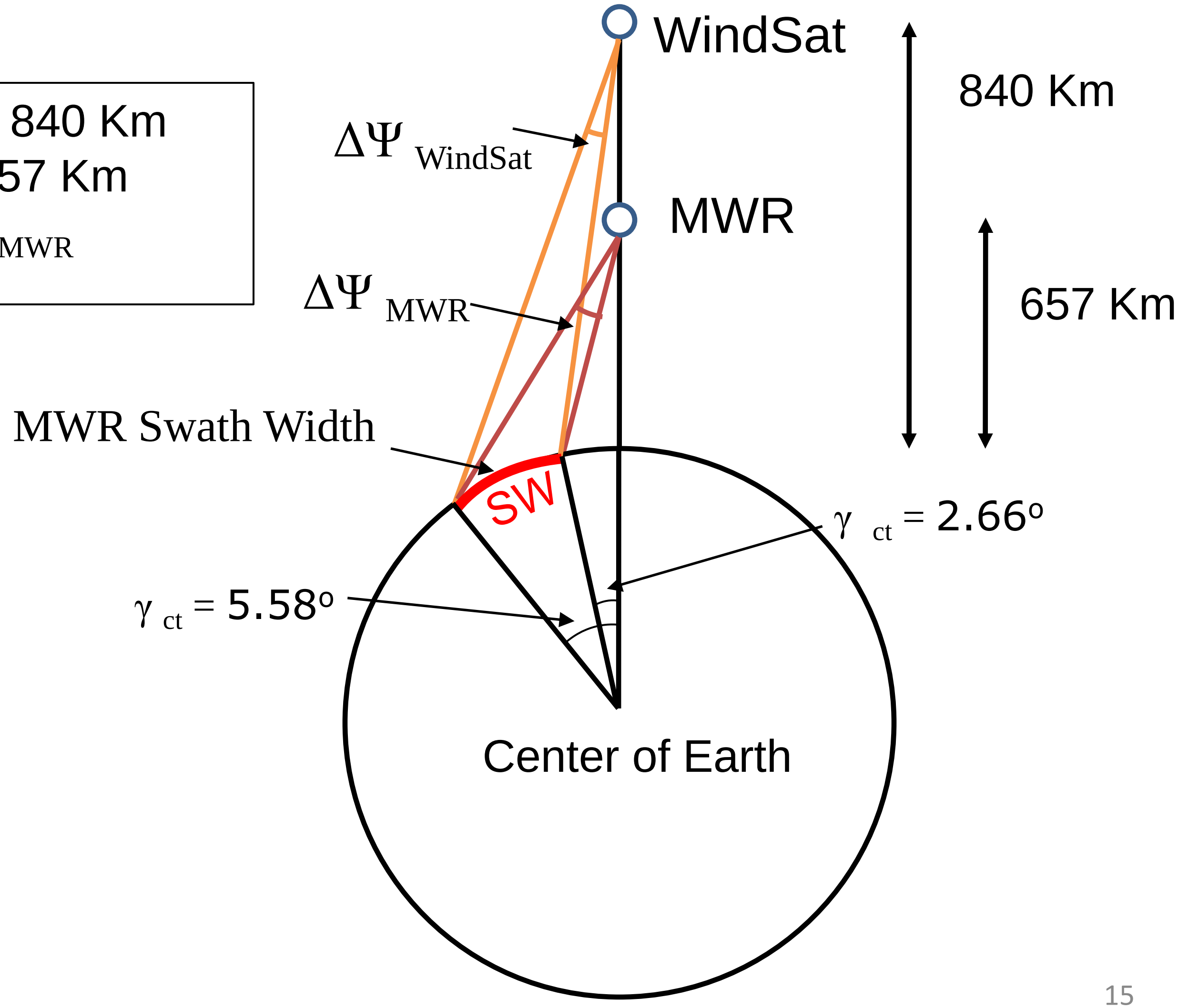
$$\text{Swath Width} = 2\rho\gamma_{ct}$$

Note: γ_{ct} is in units of radians

Note: Swath width is measured in the cross-track plane

Azimuthal Translation of MWR to Equivalent WindSat

- Altitude $_{WindSat}$ = 840 Km
- Altitude $_{MWR}$ = 657 Km
- $\Delta\Psi_{WindSat} < \Delta\Psi_{MWR}$



Satellite sub-track plane view

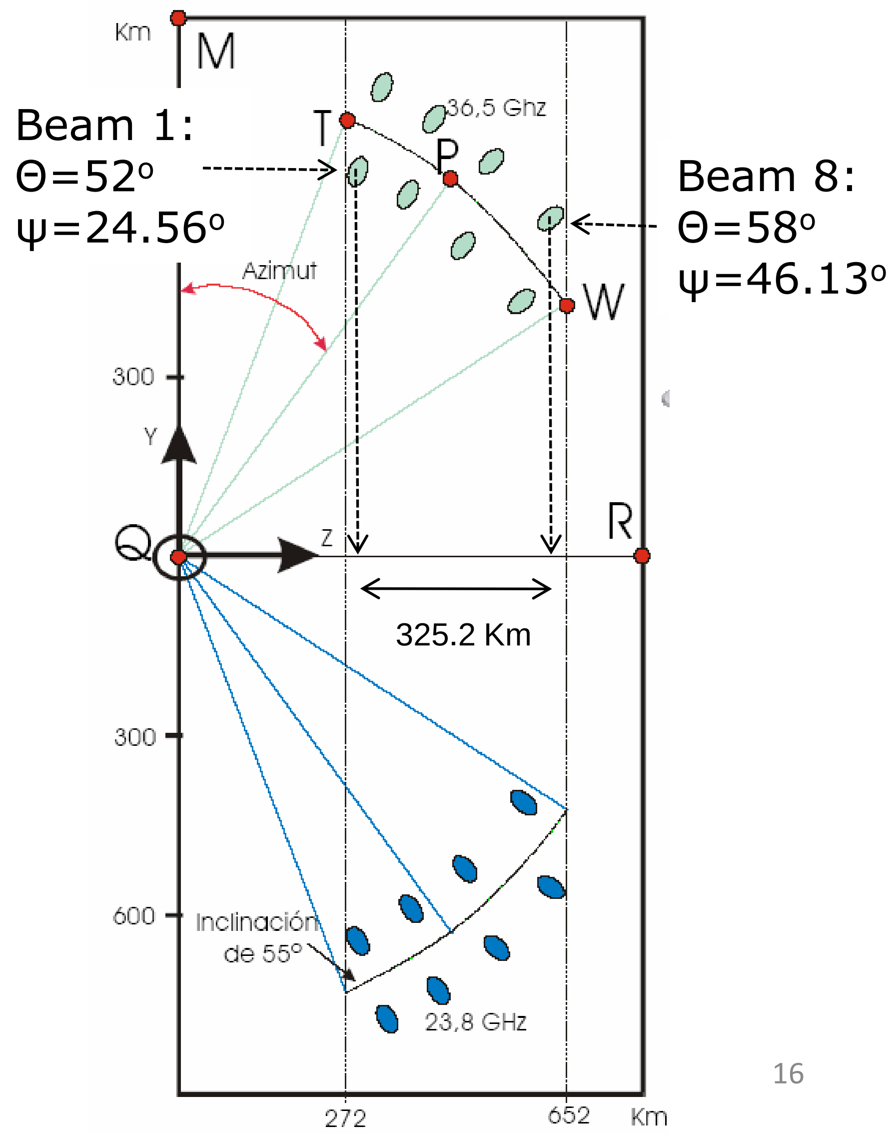
Azimuthal Translation of MWR to Equivalent WindSat cont.

- MWR swath = 272 Km to 652 Km (to right of subtrack)
  - corres $\gamma_{ct} = 2.66^{o}$ to 5.58^{o}
- Cross-track central angles (γ_{ct}) are the same for MWR and WindSat; however central angles, (γ) in the incident plane are different
  - MWR $\gamma_{58} = 7.75°$, $\gamma_{52} = 6.40°$
  - WindSat $\gamma = 8.04^{o}$
- Using the equation,

$$\sin(\gamma_{ct}) = \sin(\gamma) \times \sin(\psi)$$

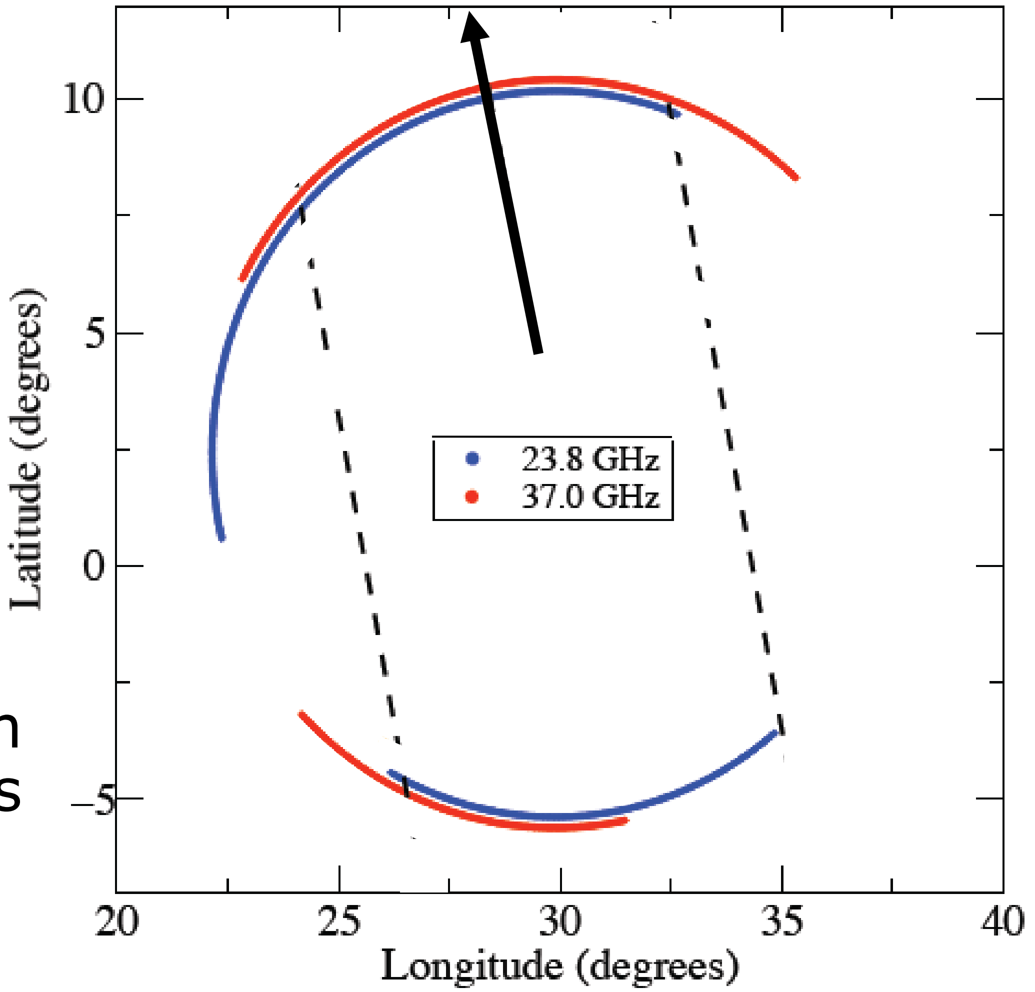
solve for corresponding WindSat azimuth angles

	Beam-1 (Az, deg)	Beam-8 (Az, deg)
MWR	24.56	46.13
WindSat	-19.37	-44.07



WindSat Azimuth Constraints

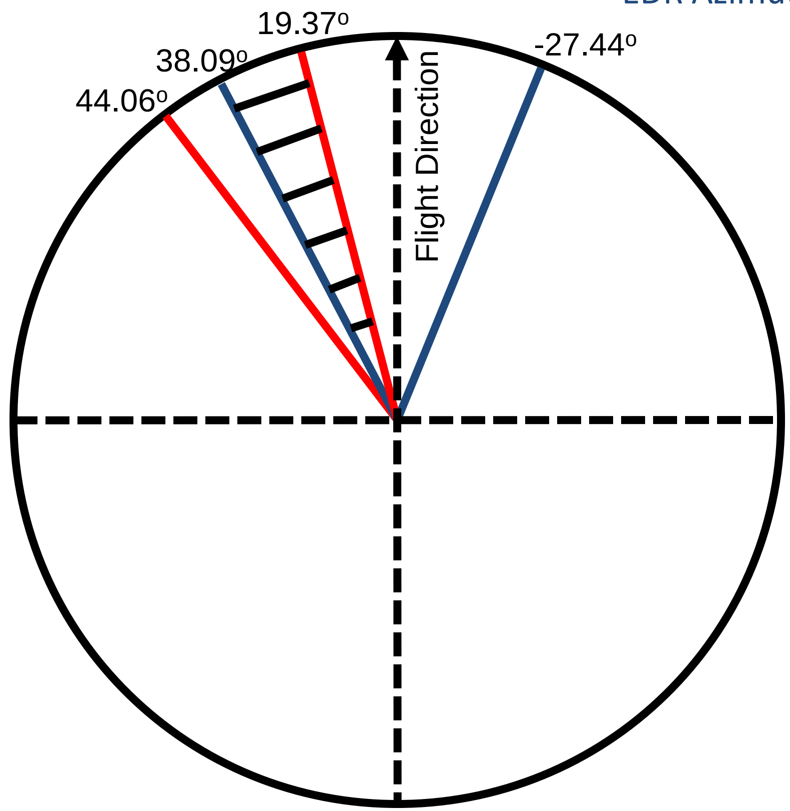
- 37 GHz azimuth range
  - Fwd: -50° to 53°
  - Aft: 125° to 183°
- 23.8 GHz azimuth range
  - Fwd: -28° to 94°
  - Aft: 142° to 211°
- For geophysical retrievals, forward and aft beams of MWR must be collocated
- Mirror the MWR swath on the left side, which offers sufficient common forward swath



WindSat Envir Data Record (EDR) Azimuth Constraints

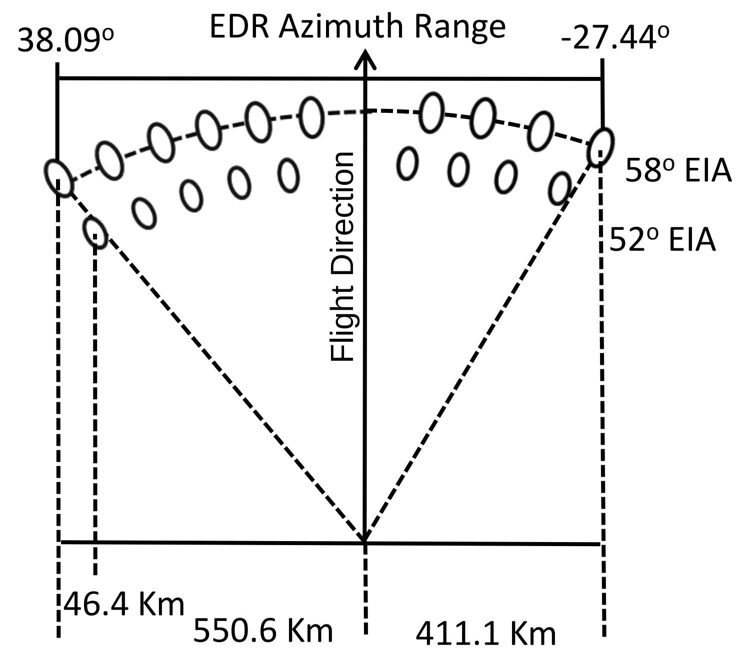
- The EDR imposes a limit on the usable azimuth angles
  - EDR azimuth range

    -27.44° to 38.09°
- Left sided MWR mirrored swath will lose ~6° in azimuth; therefore swath is shifted to start from 38.09°
- Additional MWR beams generated using the entire azimuth range of EDR



WindSat EDR Azimuth Constraints

- A total of 19 MWR beams have been simulated
  - 11 on the left & 8 on the right side of flight direction
- Left most MWR beam corres to swath width of 550.6 Km & right most corres to 411.1 Km
- The beam center to center swath spacing corres exactly to MWR spacing = 46.4 Km (325.2/ 7)
- Accurate spatial & sampling resolution of MWR
- Accurate orientation by change in azimuth



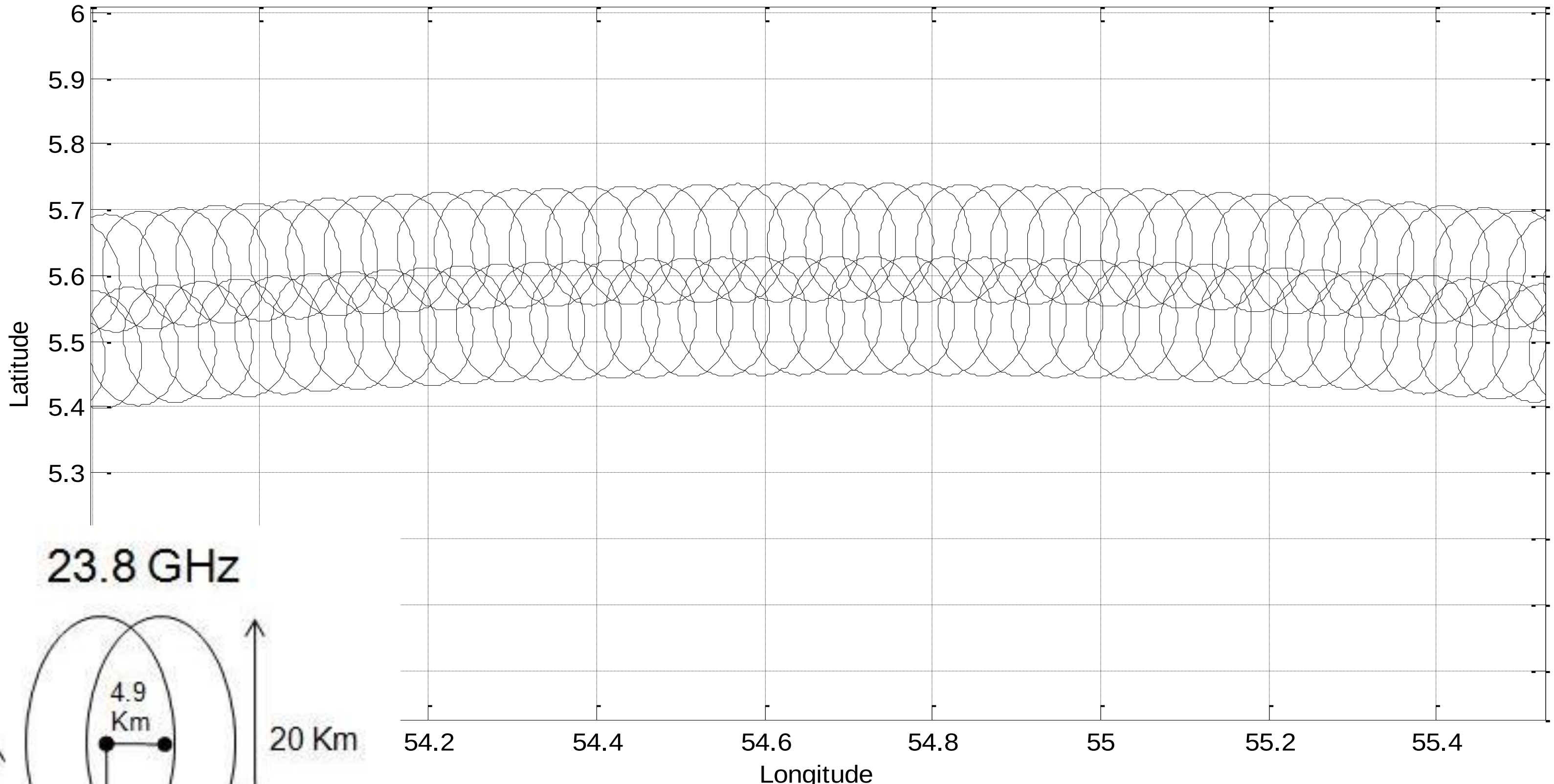
•Beam Azimuth Angle:

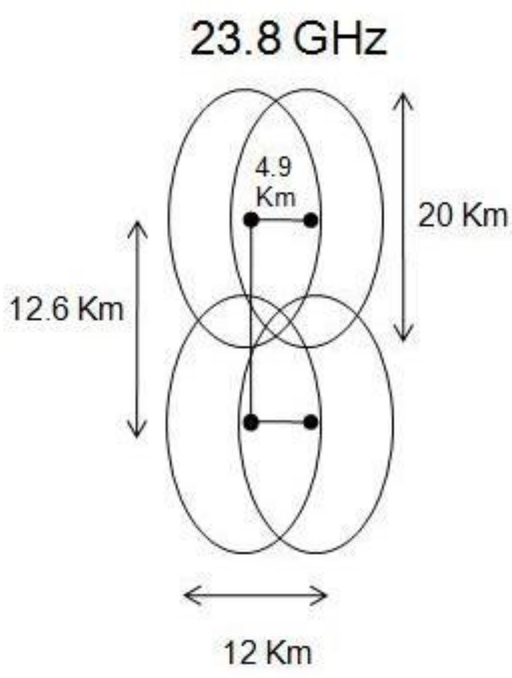
$$\gamma_{ct} = \text{Swath width} / \rho$$

$$\Psi_{beam} = \sin^{-1}(\sin(\gamma_{ct})/\sin(\gamma_{WindSat}))$$

•The 8 beams on either side of flight direction are symmetrical by azimuth

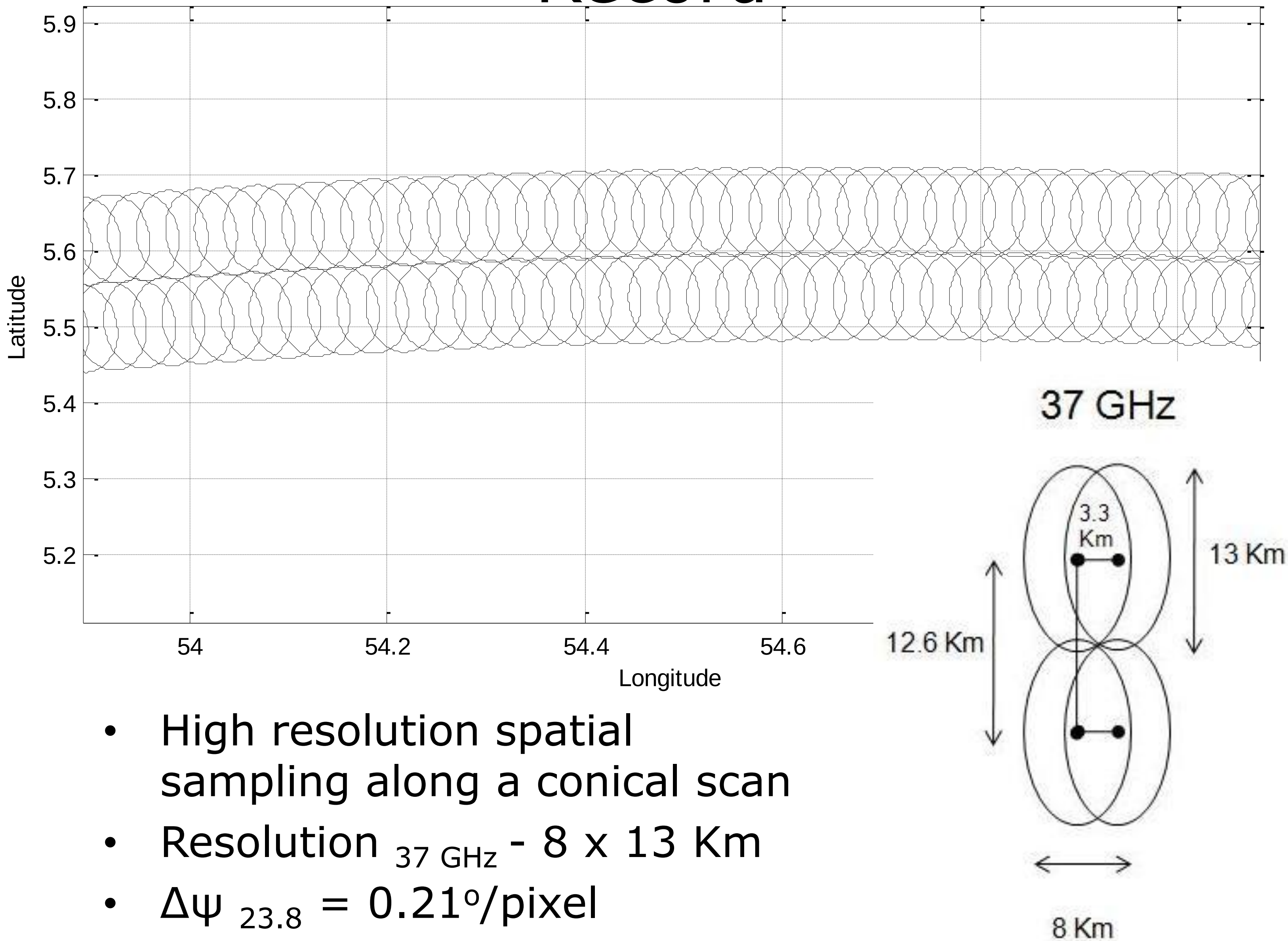
23.8 GHz WindSat Intermediary Data Record





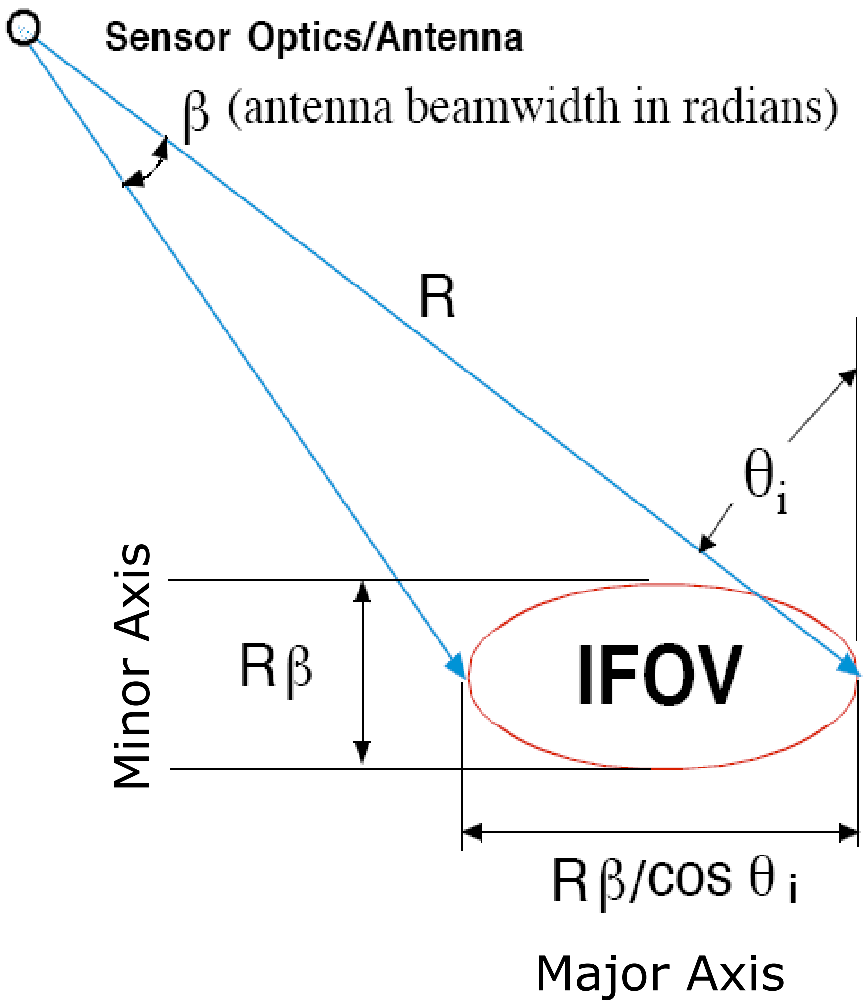
- High resolution spatial sampling along a conical scan
- Resolution $_{23\ \text{GHz}}$ - 12 x 20 Km
- $\Delta\psi_{23.8} = 0.313^{o}$/pixel

37 GHz WindSat Intermediary Data Record



- High resolution spatial sampling along a conical scan
- Resolution $_{37\ \mathrm{GHz}}$ - 8 x 13 Km
- $\Delta\psi_{23.8} = 0.21^{o}$/pixel

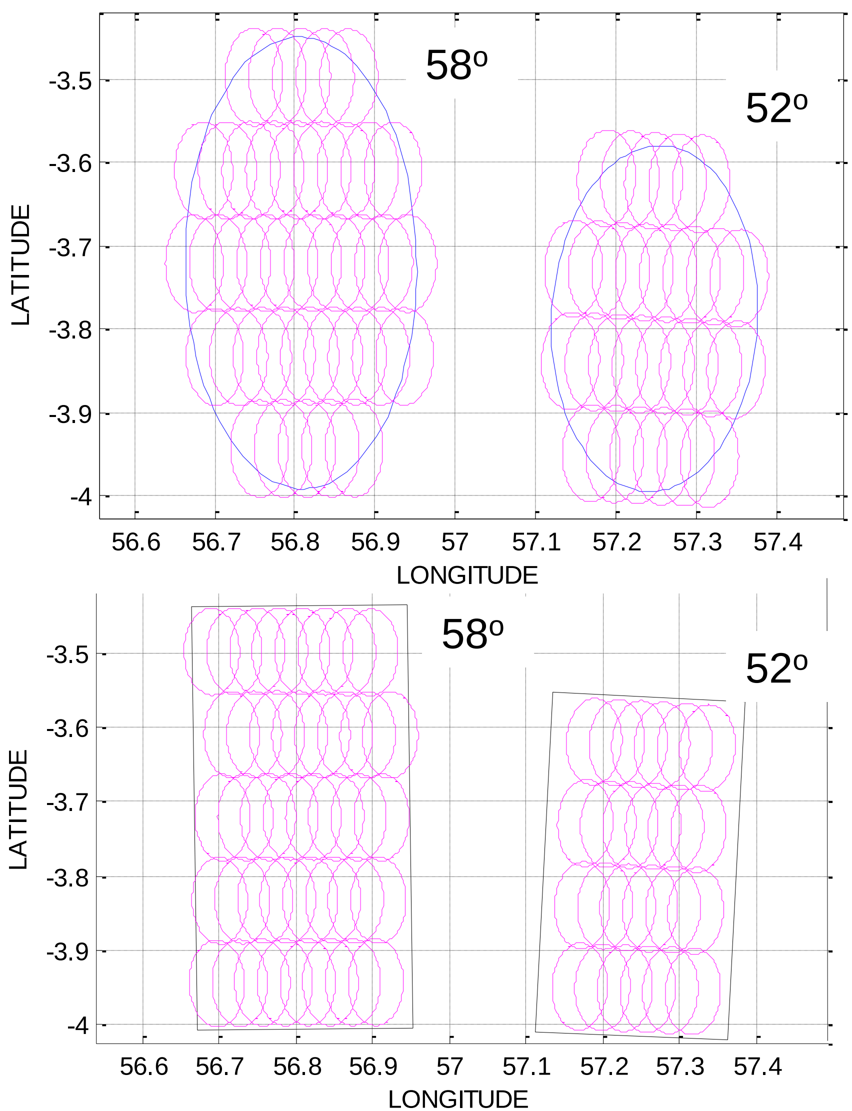
MWR IFOV Geometry



- MWR footprint dimensions
- $\Theta = 52^o$ & 58^o
- 3 dB beam width, $\beta = 1.64^o$
- Slant range:
  - $R_{58} = 1118.6$ Km
  - $R_{52} = 995.8$ Km

Incidence Angle	Minor Axis (Km)	Major Axis (Km)
52°	28.5	46.3
58°	32	60.4

37 GHz IDR Beam-Fill in MWR IFOV

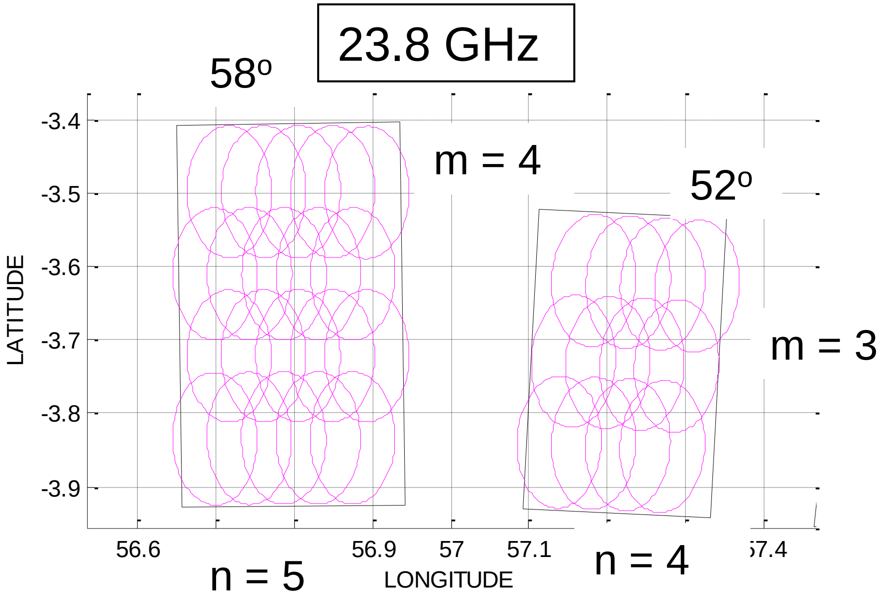


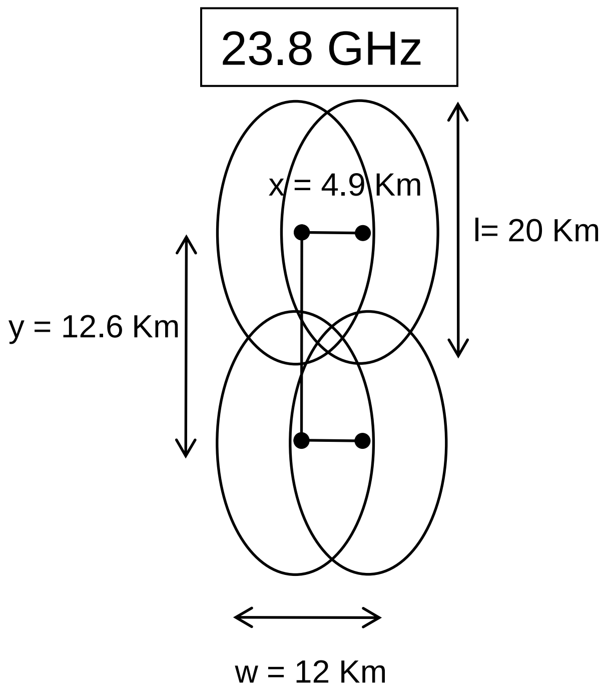
- Number of along-scan IDR pixels falling into an elliptical footprint varies along ellipse major axis

- Complexity is reduced using a rectangular footprint

- Rectangular footprint has equal number of along-scan IDR pixels for all scans

23.8 GHz IDR Beam-Fill in MWR IFOV cont.





- The IDR pixels falling into a rectangular footprint, along-scan & along-track, are calculated with the following equations

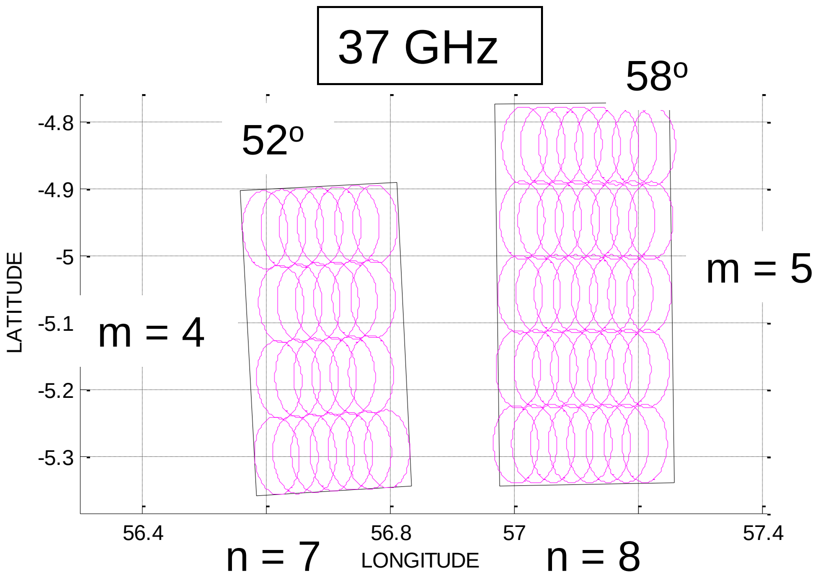
$$n = ((MinorAxis - w)/x) + 1$$

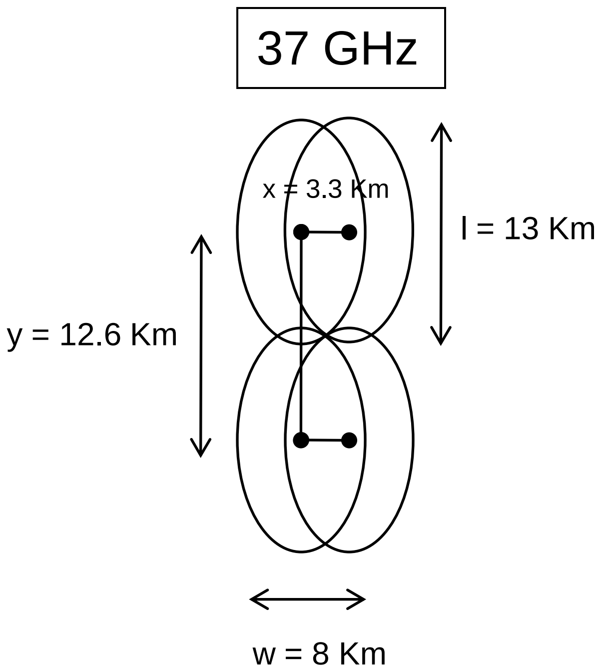
$$m = ((MajorAxis - l)/y) + 1$$

- 'n' is the integer # of IDR pixels along-scan while 'm' is integer the # of IDR scans

Incidence Angle	Minor Axis (Km)	Major Axis (Km)	n	m
52º	28.5	46.3	4	3
58º	32	60.4	5	4

37 GHz IDR Beam-Fill in MWR IFOV cont.





- The IDR pixels falling into a rectangular footprint, along-scan & along-track, are calculated with the following equations

$$n = ((MinorAxis - w)/x) + 1$$

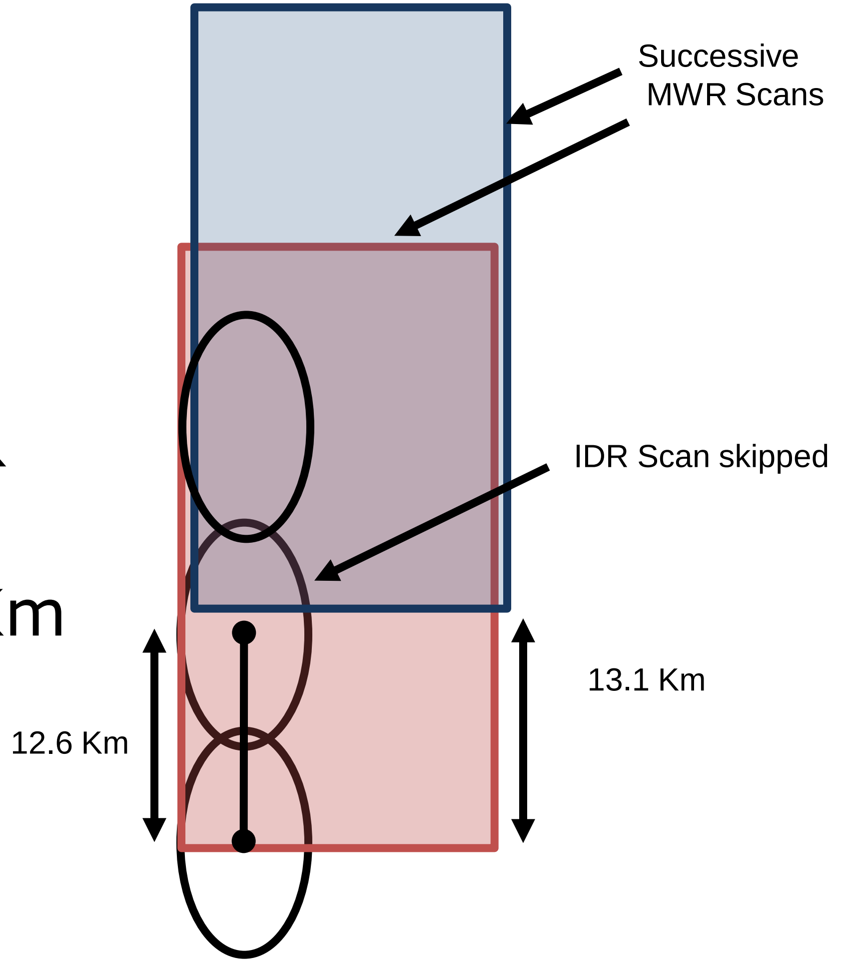
$$m = ((MajorAxis - l)/y) + 1$$

- 'n' is the integer # of IDR pixels along-scan while 'm' is the integer # of IDR scans

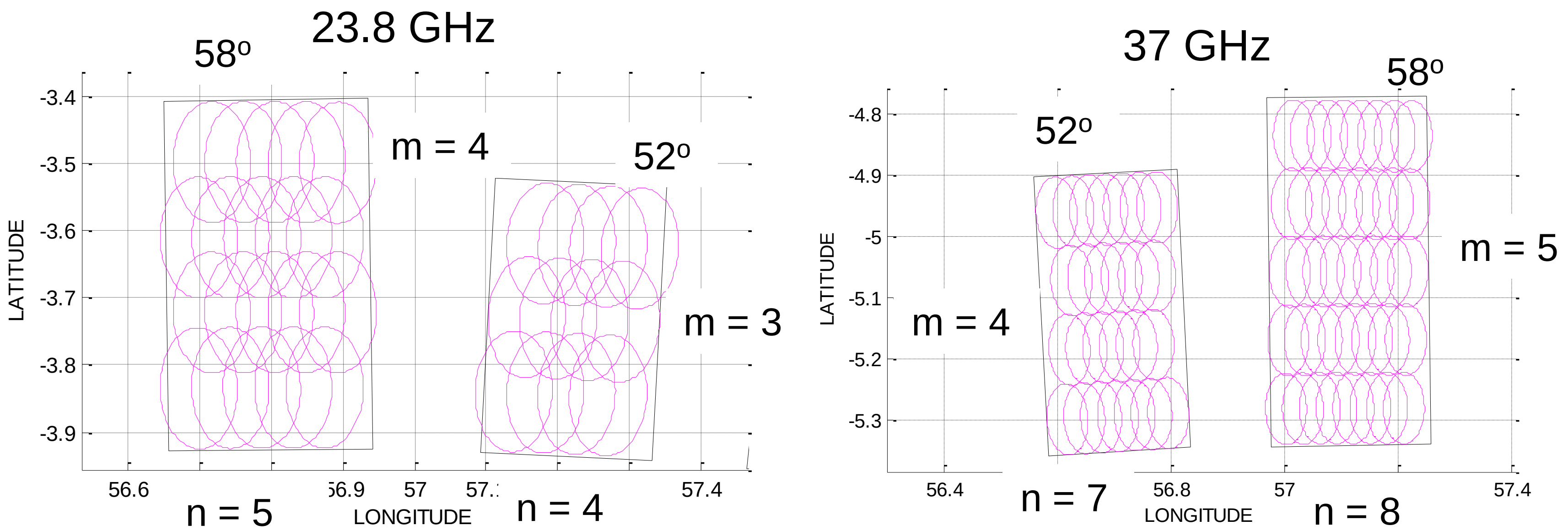
Incidence Angle	Minor Axis (Km)	Major Axis (Km)	n	m
52°	28.5	46.3	7	4
58°	32	60.4	8	5

IDR Scan Mapping into MWR Pixels

- MWR Inter-scan distance = 13.1 Km
- IDR Inter-scan distance = 12.6 Km
- Difference = 0.5 Km; therefore periodically an IDR scan will be skipped
- This period is 12.6 Km/0.5 Km = 25.2 scans

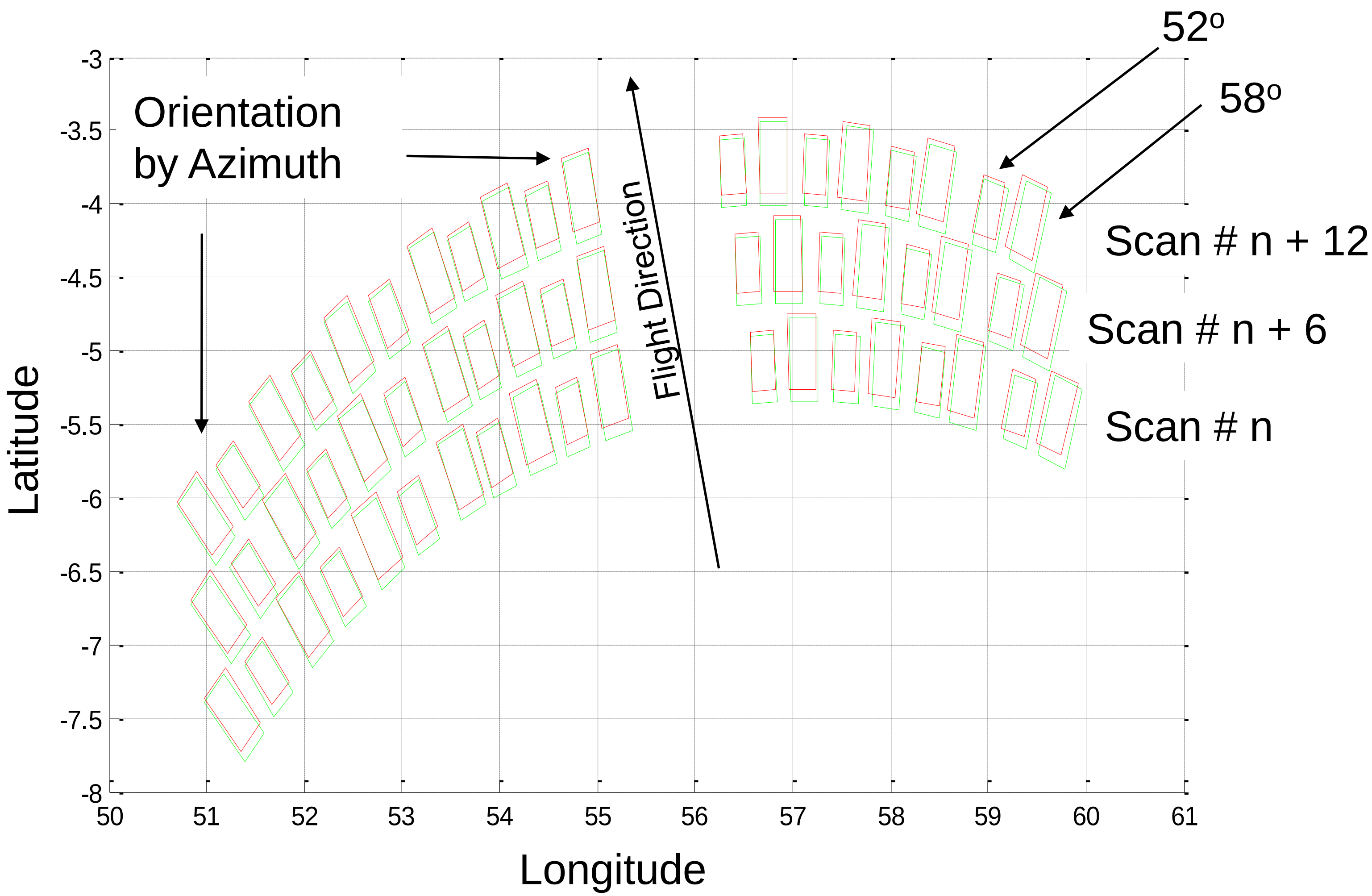


MWR IFOV Summary



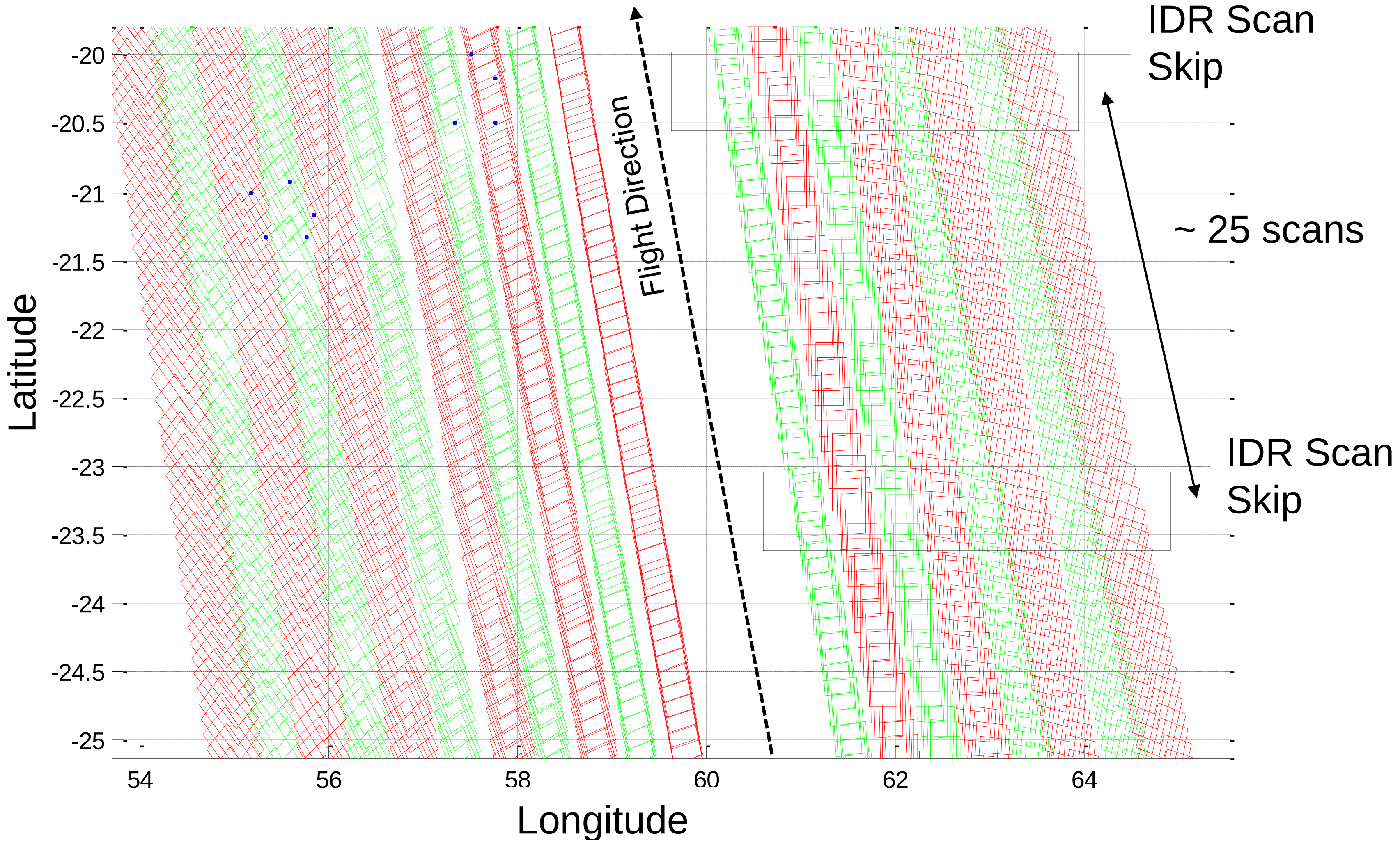
Frequency	Incidence Angle	Width (Km)	Length (Km)	IDR Pixels n (Across Track)	IDR Scans m (Along Track)
23.8 GHz	58º	31.6	57.8	5	4
	52º	26.7	45.2	4	3
37 GHz	58º	31.1	63.4	8	5
	52º	27.8	50.8	7	4

MWR Pixel Collocations

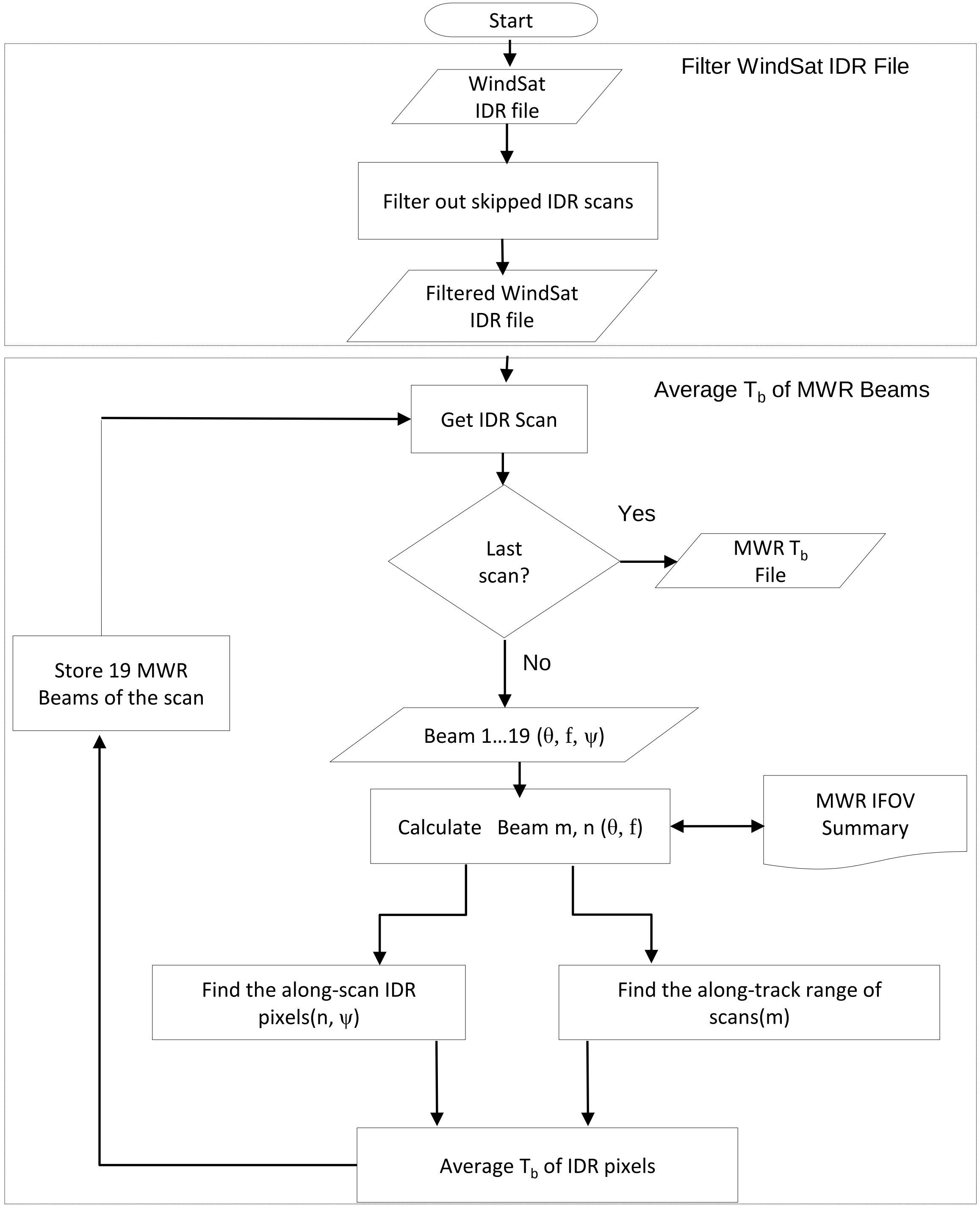


Collocated 23.8 (Green) & 36.5 (Red) GHz Beams

MWR 37 GHz Pixels

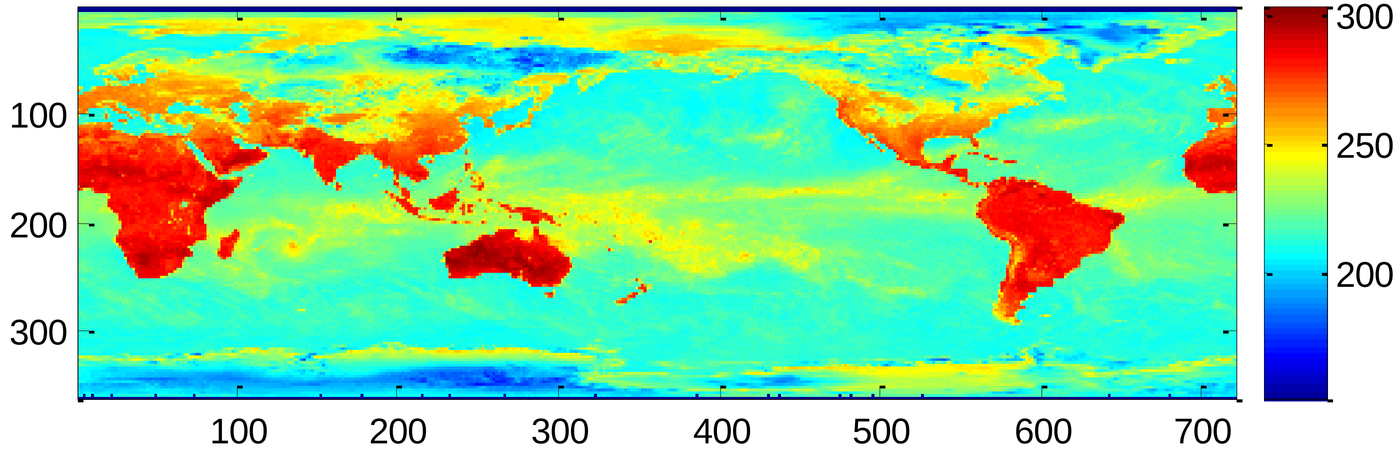


MWR 36.5 GHz Swath at 58° (Red) & 52° (Green)

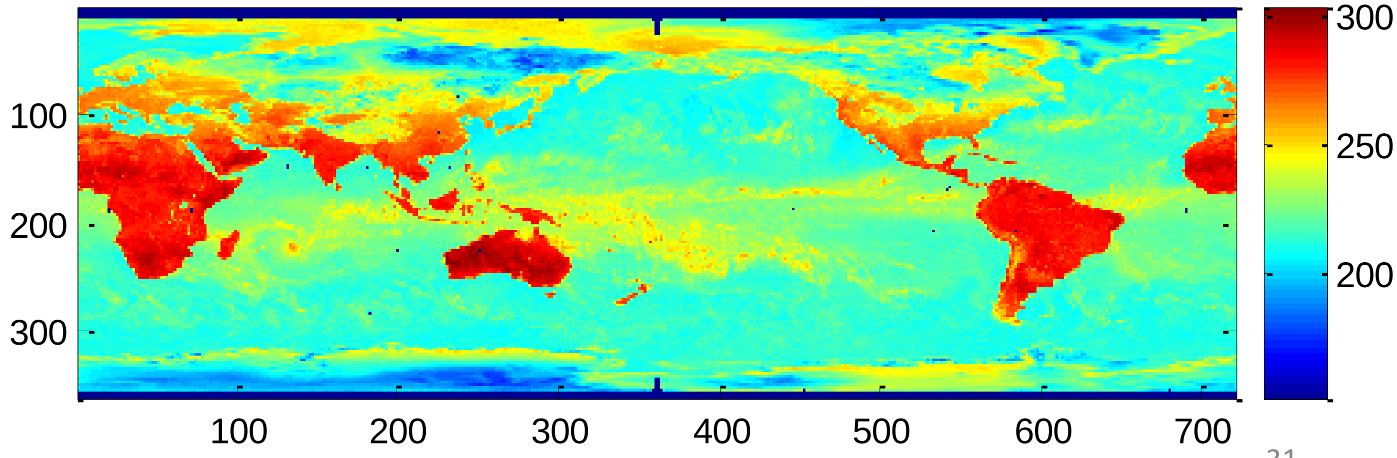

Start
Filter WindSat IDR File
WindSat
IDR file
Filter out skipped IDR scans
Filtered WindSat
IDR file
Average T_b of MWR Beams
Get IDR Scan
Last
scan?
Yes
MWR T_b
File
No
Store 19 MWR
Beams of the scan
Beam 1…19 (θ, f, ψ)
Calculate Beam m, n (θ, f)
MWR IFOV
Summary
Find the along-scan IDR
pixels(n, ψ)
Find the along-track range of
scans(m)
Average T_b of IDR pixels

Comparison of WindSat & MWR T_b at 37 GHz (V-pol) @ 53 deg

- 0.5^0 resolution
- T_b average of 68 obits in Feb 2007
- Shows radiometric accuracy of the T_b simulation
- Mean ΔT_b = 0 K
- σ ΔT_b = ~2 K



WindSat T_b



MWR T_b

T_b Normalization

- WindSat Tb normalizations are required for incidence angle & frequency adjustment
  – WindSat operates at 23.8 - & 37-GHz @ 53˚
  – MWR operates at 23.8 - & 36.5-GHz @ 52˚ & 58°
- Radiative Transfer Model (RTM) was used to transform WindSat T_b measurements to equivalent MWR frequencies and incidence angles

WindSat Normalization Procedure

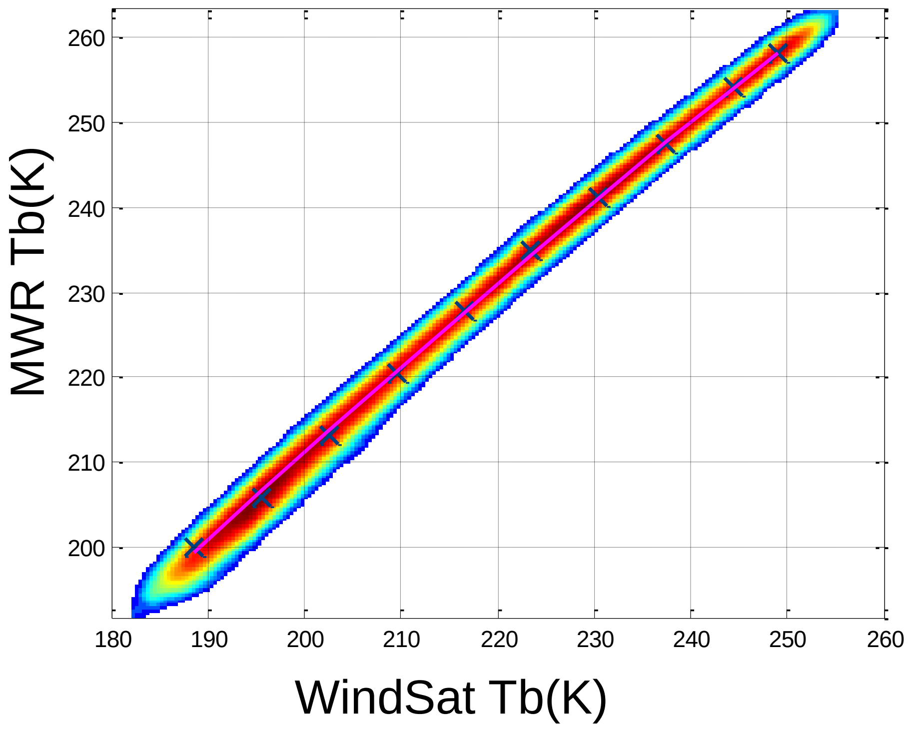
- Run RTM
  - Calculate theoretical MWR T_b for environmental parameters (1° box)
    - Tb $_{(MWR\text{-}perdicted)}(f_{MWR}, \Theta_{MWR}, WS, SST, WV, CLW)$
      - Frequency = 23.8- & 36.5 GHz
      - Incidence angle = 52˚ & 58˚
  - Calculate theoretical WindSat T_b for environmental parameters (1° box)
    - $Tb_{(WS\text{-}perdicted)}(f_{WS}, \Theta_{WS}, WS, SST, WV, CLW)$
      - Frequency = 23.8- & 37 GHz
      - Incidence angle = 53˚

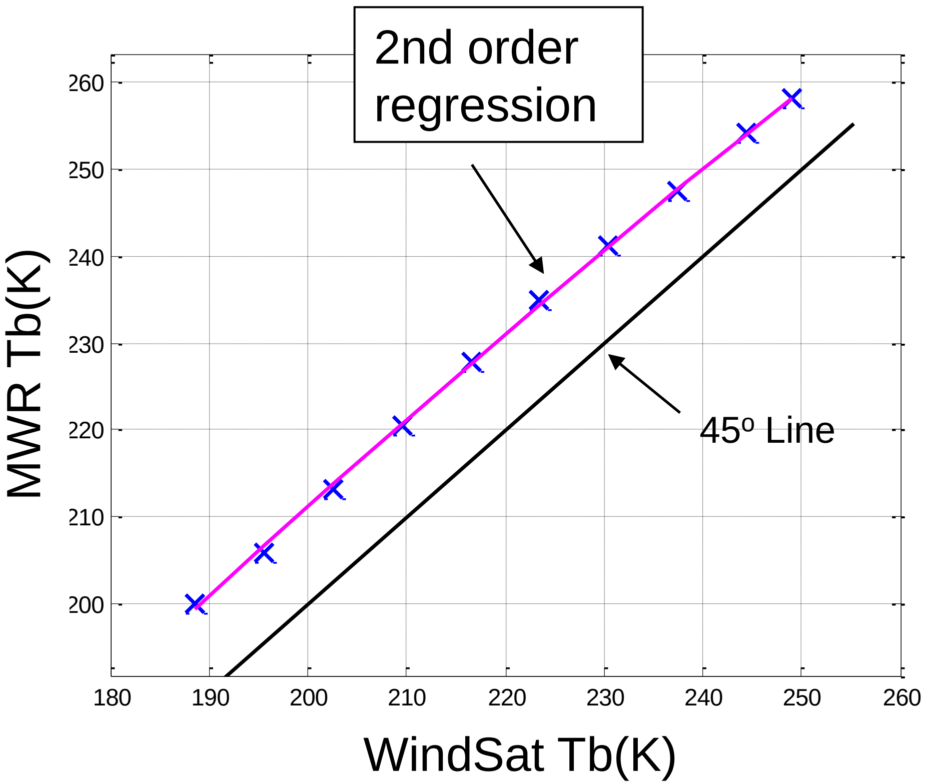
Expected Delta Tb (MWR to WindSat)

– Calculate the predicted (theoretical) Tb difference between MWR & WindSat
    - delta = $MWR_{predicted} – WS_{predicted}$

$$T_{b\ MWR} = WindSat_{(measured)} + delta$$

T_b Normalization of 23.8 V Channel (58º)

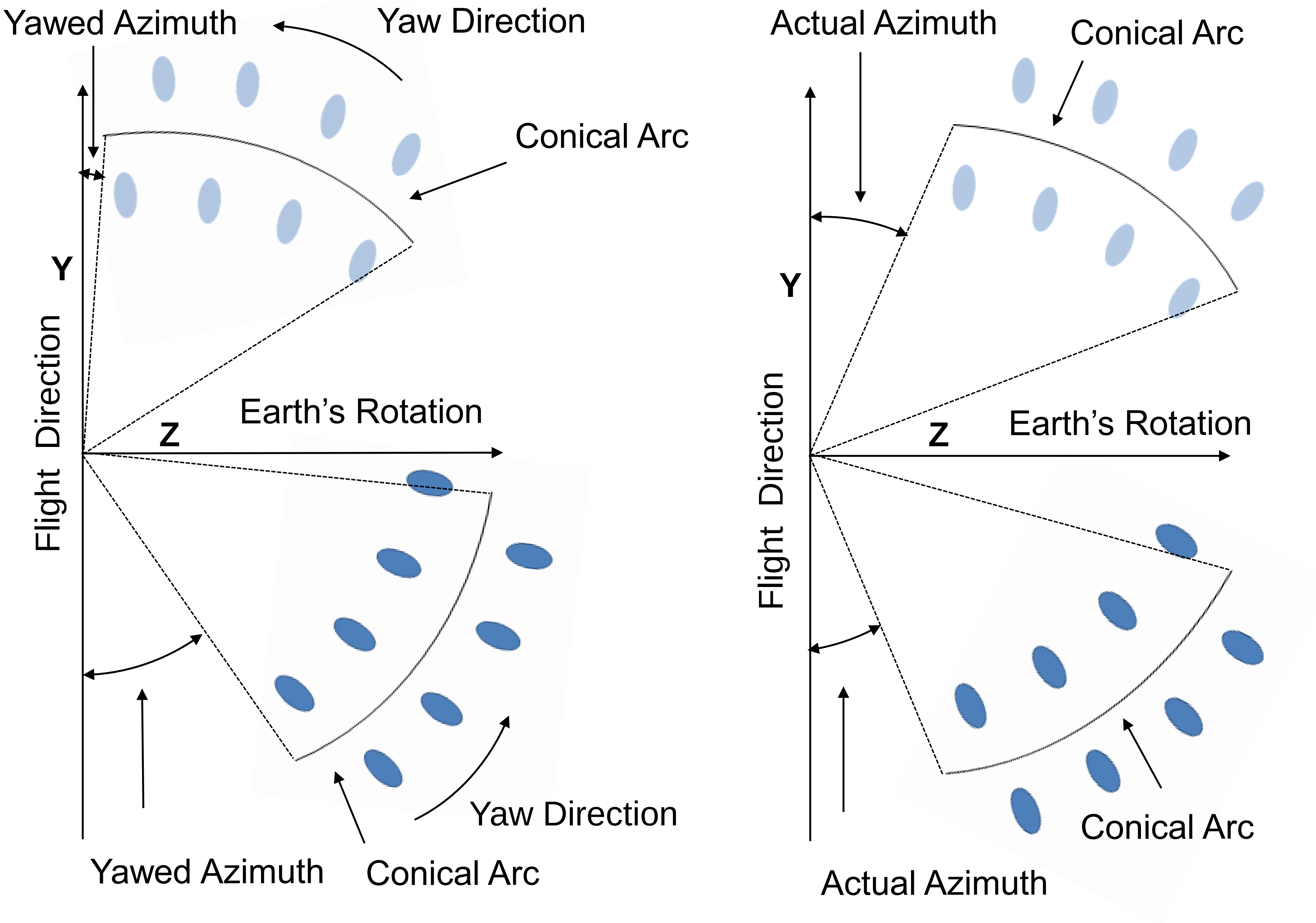




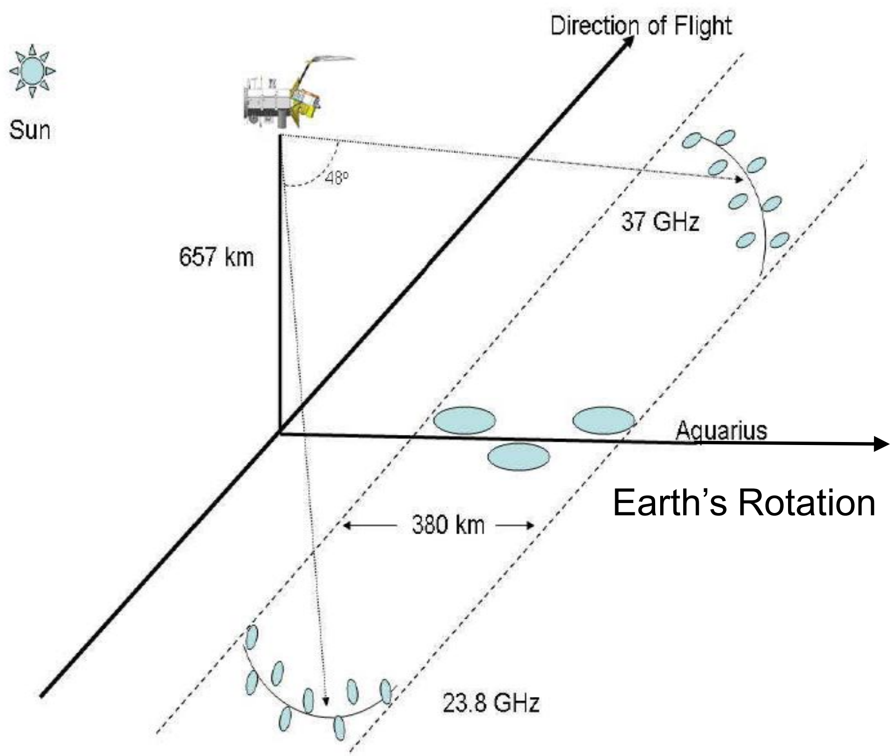
- Ran RTM for 1 week to calculate WindSat & MWR theoretical T_b s
- $T_{b\ (theoretical)}$ (f, ϴ, WS,SST,WV,CLW), envr. parameters from GDAS
- T_b normalizations were done for all channels (23.8 V, 36.5 V & H) at 52º & 58º incidence angles
- The Tb Biases were found to be independent of the environmental variables

Yaw Steering Results

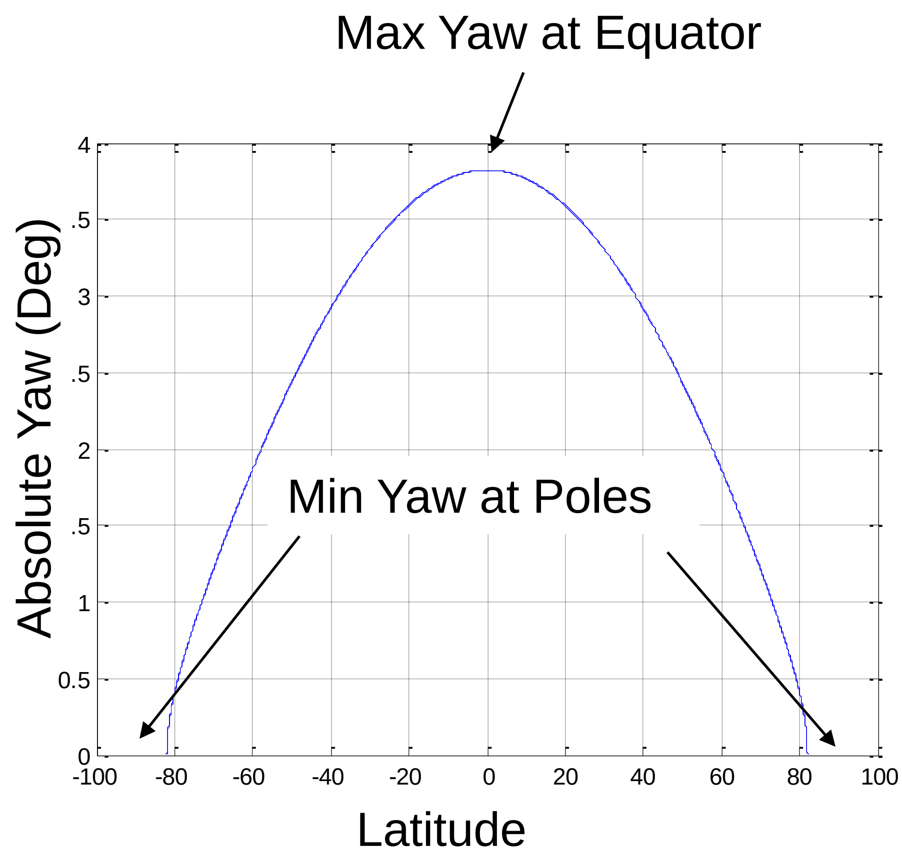
Aquarius/SAC-D Yaw Steering



Aquarius/SAC-D Yaw Steering



Collocated MWR & Aquarius Swath

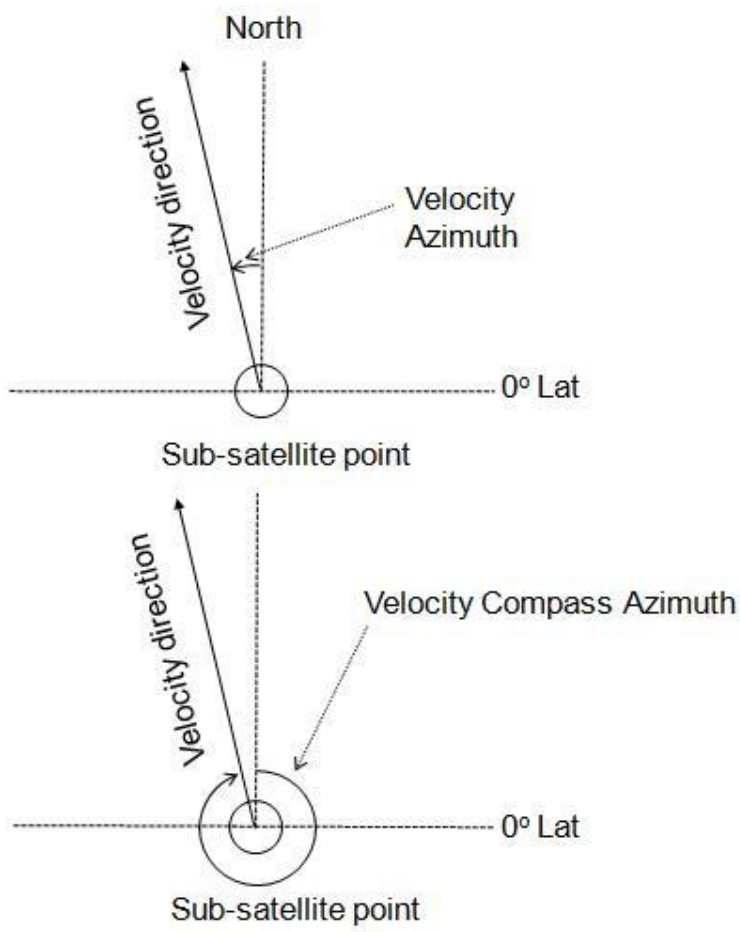


Absolute Yaw as a function of Latitude (Provided by CONAE)

Evaluation Procedure

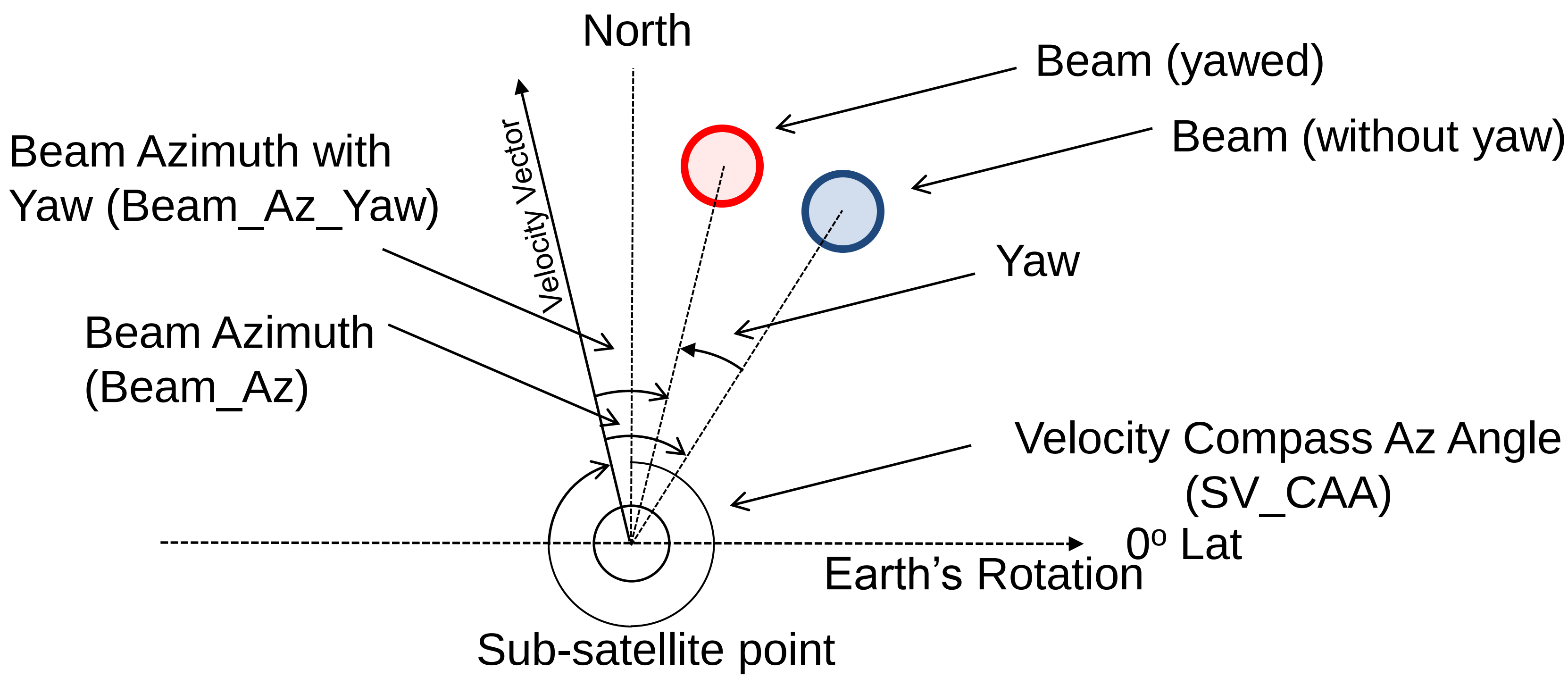
- Used STK to simulate SAC-D orbit (Inclination 98^{o}, Eccentricity = 0, Altitude = 657 Km) & generated:
  - SSPs
  - Satellite Velocity Azimuth (relative to North)
  - @ 0.24 sec time step
- Generated corresponding pairs of forward/aft beam points sequentially for 8 pairs@ 0.24 sec step, using:
  - SubSat Point (SSP) (lat, lng)
  - Earth Central Angle (γ) b/w SSP & beam boresight
  - Beam Compass Azimuth (+ Yaw @ SSP_lat)

Evaluation Procedure cont.



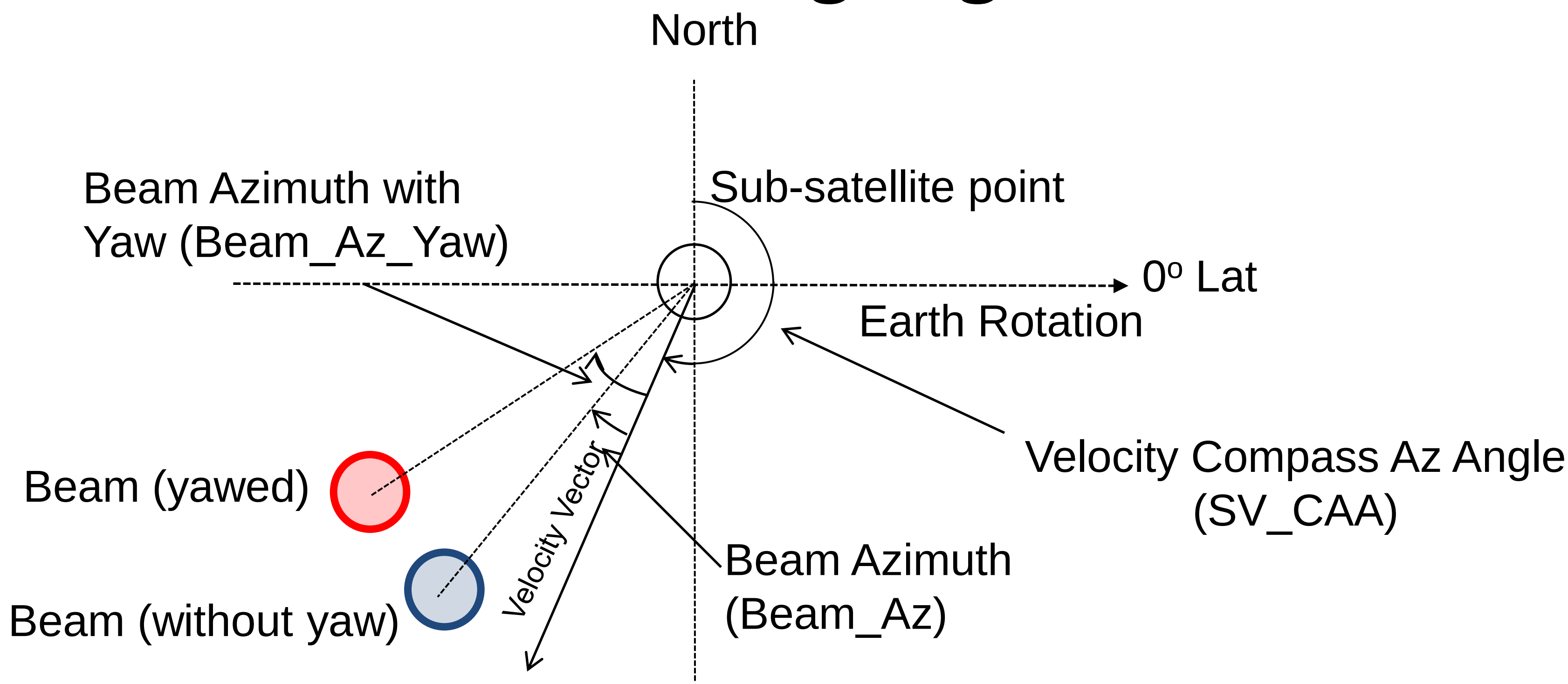
Satellite Velocity Azimuth

Beam Compass Azimuth Angle for Ascending Flight

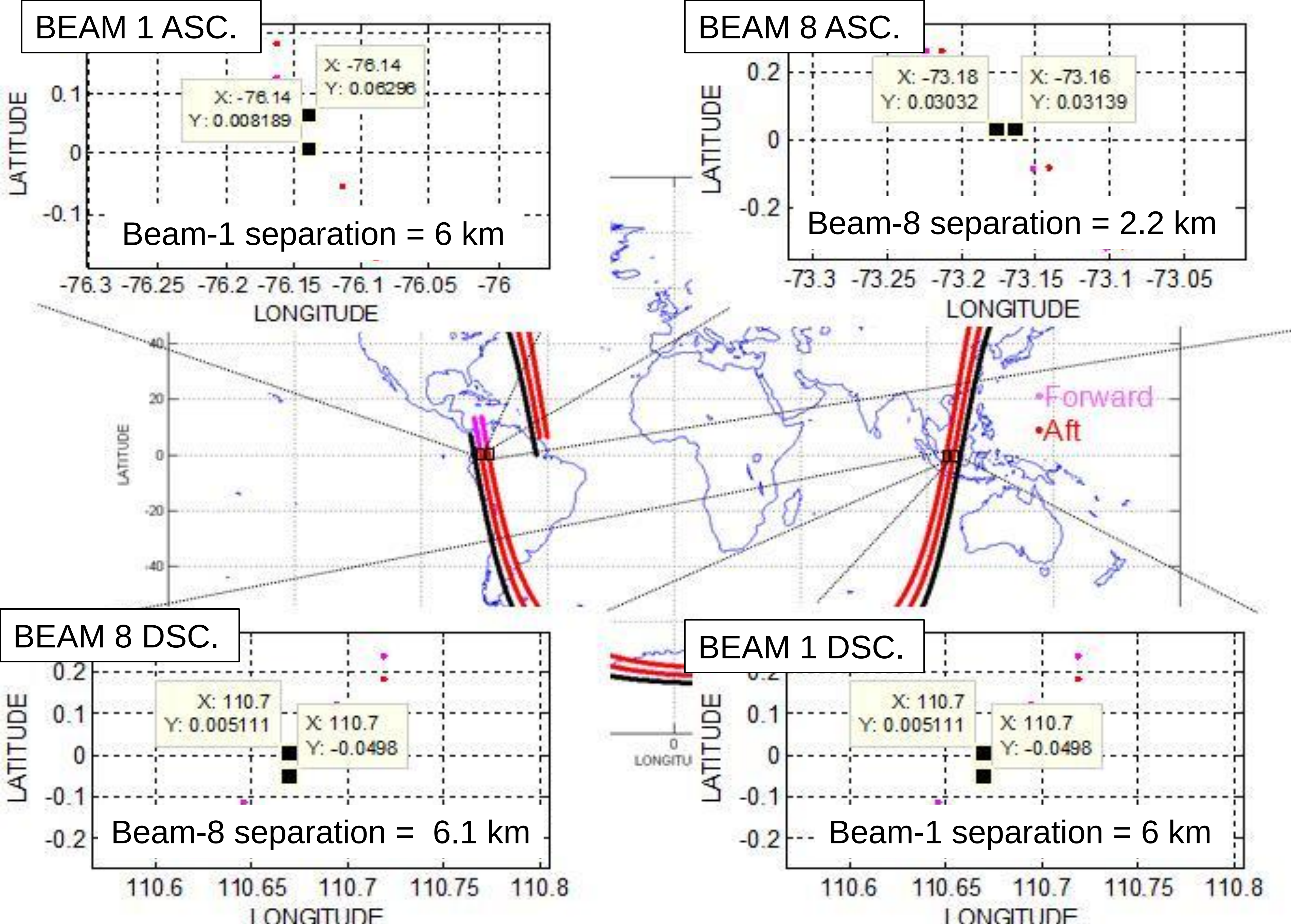


Beam_CAA_Yaw = modulo ((SV_CAA + Beam_Az + Yaw), 360)

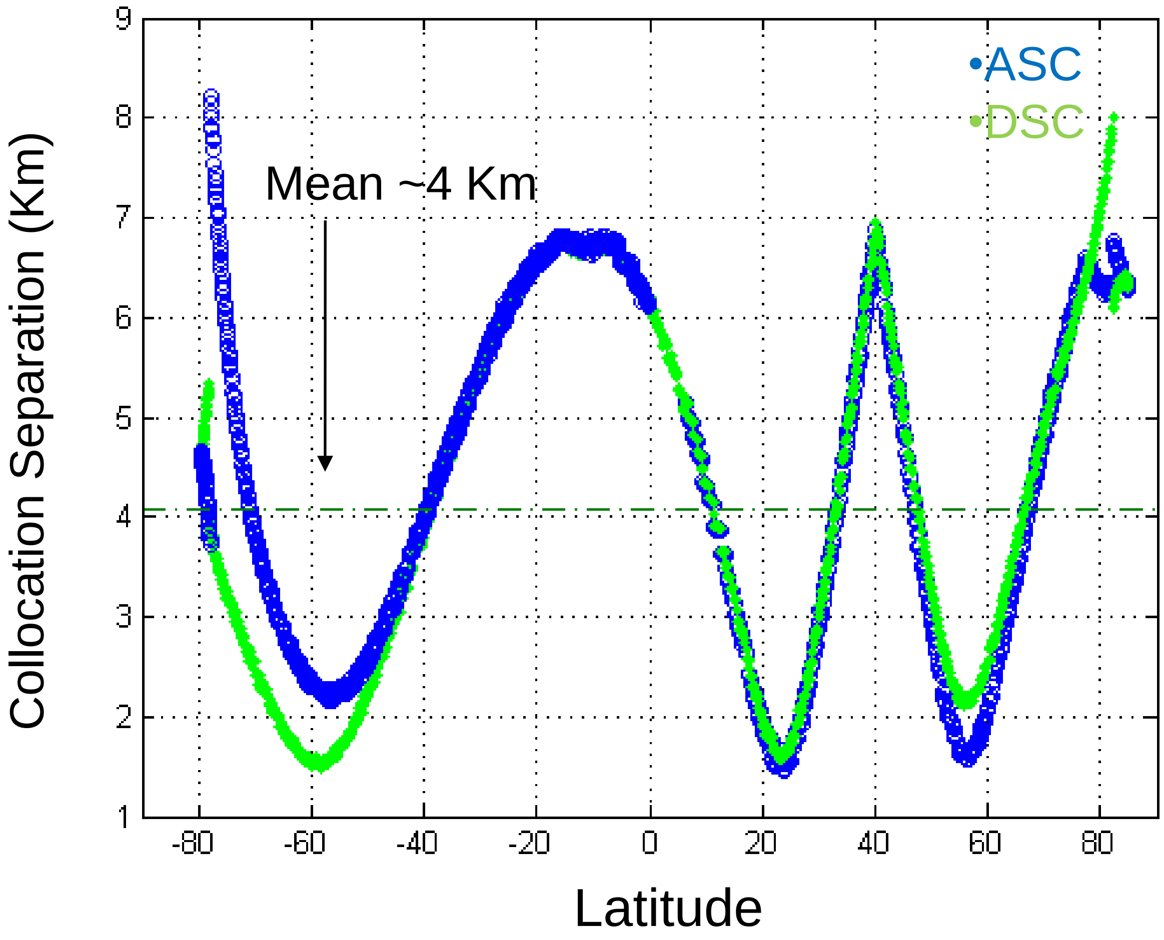
Beam Compass Azimuth Angle for Descending Flight



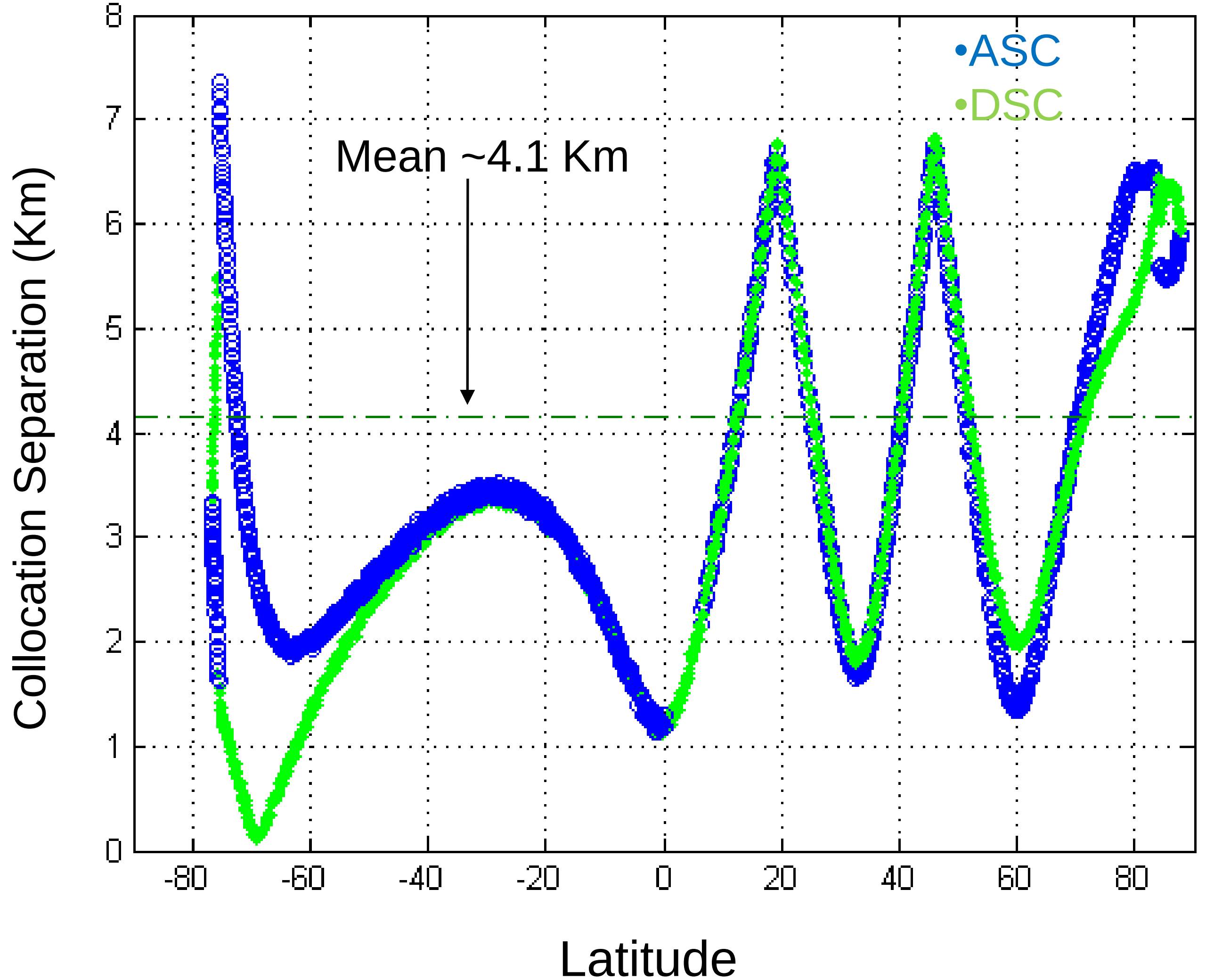
Beam_CAA_Yaw = modulo ((SV_CAA + Beam_Az + Yaw), 360)


BEAM 1 ASC.
X: -76.14
Y: 0.06296
X: -76.14
Y: 0.008189
Beam-1 separation = 6 km
LATITUDE
LONGITUDE
BEAM 8 ASC.
X: -73.18
Y: 0.03032
X: -73.16
Y: 0.03139
Beam-8 separation = 2.2 km
LATITUDE
LONGITUDE
•Forward
•Aft
BEAM 8 DSC.
X: 110.7
Y: 0.005111
X: 110.7
Y: -0.0498
Beam-8 separation = 6.1 km
LATITUDE
LONGITUDE
BEAM 1 DSC.
X: 110.7
Y: 0.005111
X: 110.7
Y: -0.0498
Beam-1 separation = 6 km
LATITUDE
LONGITUDE

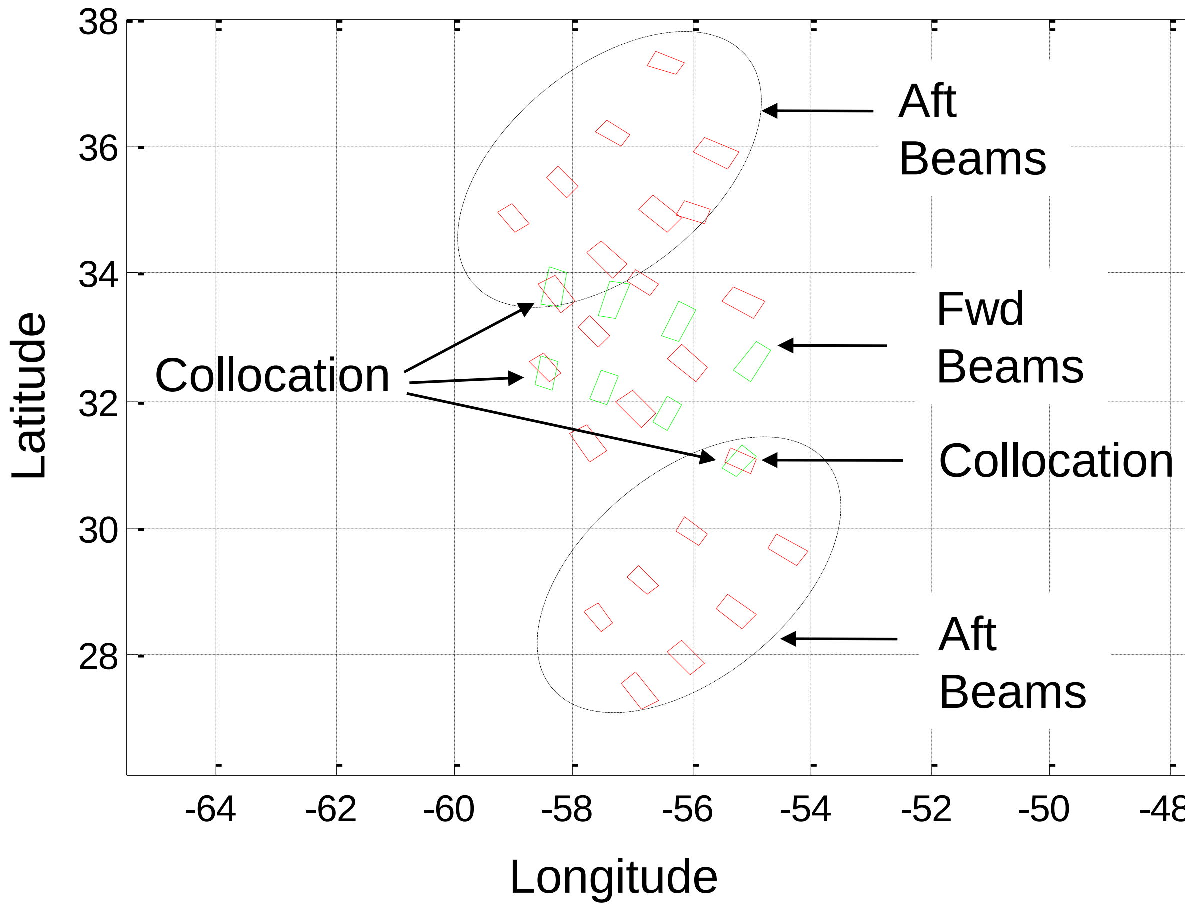
Forward/Aft Beam-1 Collocation Separation



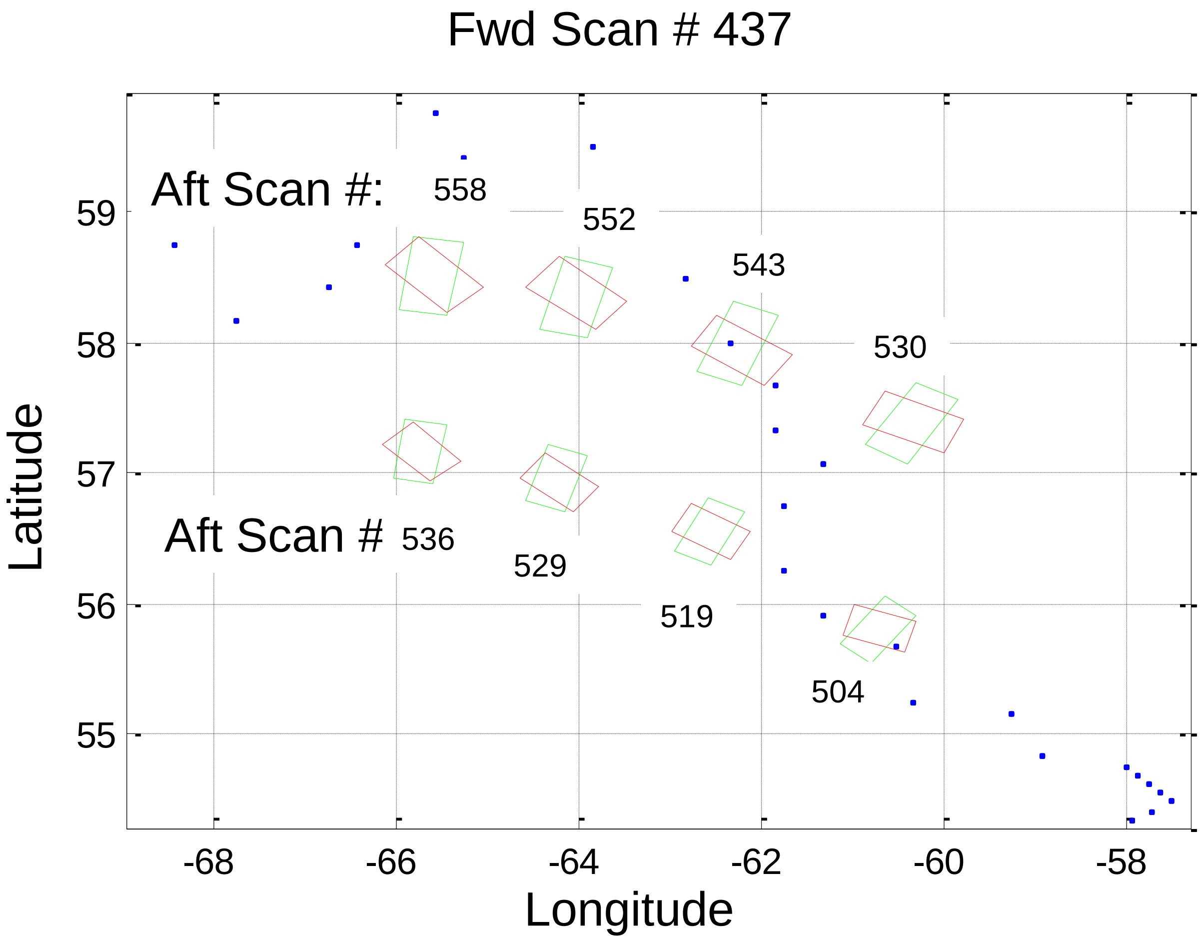
Forward/Aft Beam-8 Collocation Separation



A Snapshot of 3 Forward Beams Collocating



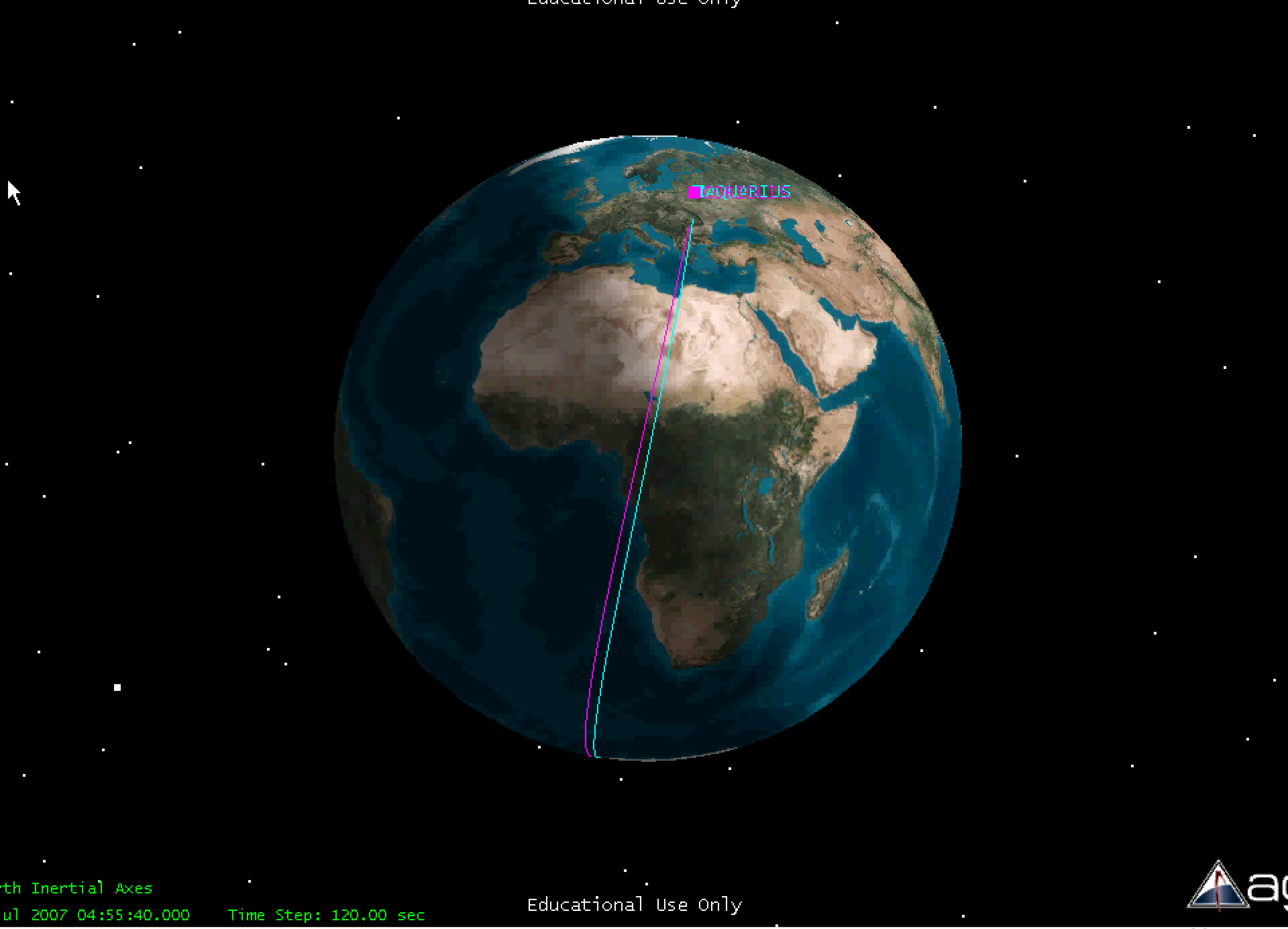
All Forward Beams Collocating with Different Aft Scans

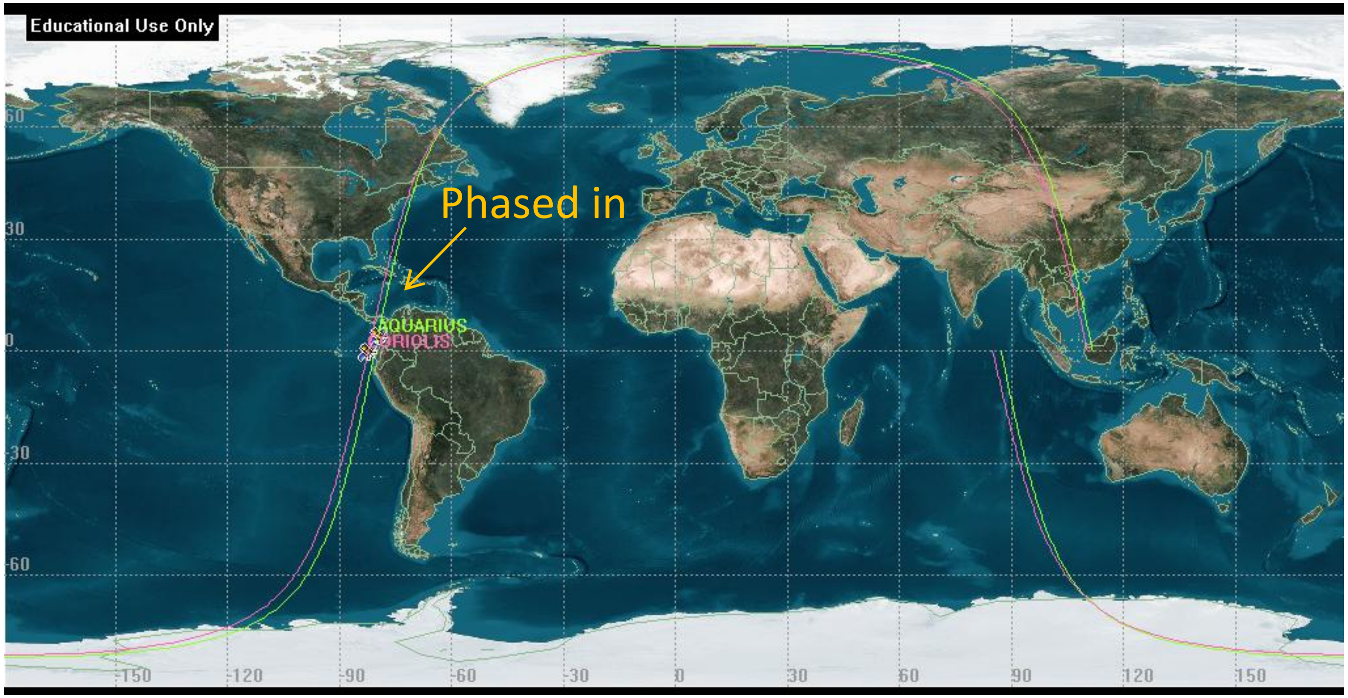


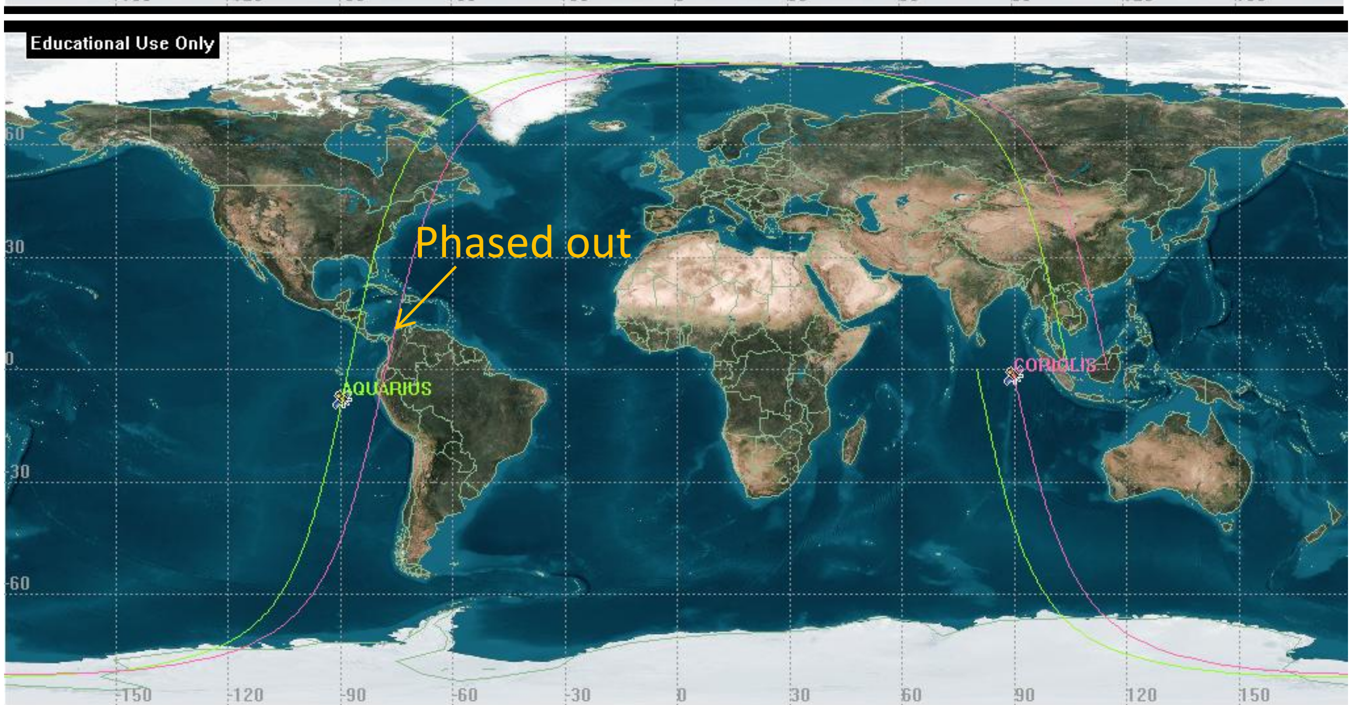
Post-launch Inter-Satellite Radiometric Calibration using WindSat

WindSat shares similarities in orbit (ground track), radiometer frequencies and swath overlap with MWR

Parameter	WindSat	MWR
Altitude	840 Km	657 Km
Eccentricity	0.00134	0.0012
Inclination Angle	98.7^o	98.01^o
Ascending Node	6 p.m.	6 p.m.
Frequency	23.8 (V & H) and 37.0 (V & H)	23.8 (V) and 36.5 (V & H) GHz
Swath Width	~950 Km	~380 Km
Earth Incidence Angle	53^o	52^o & 58^o

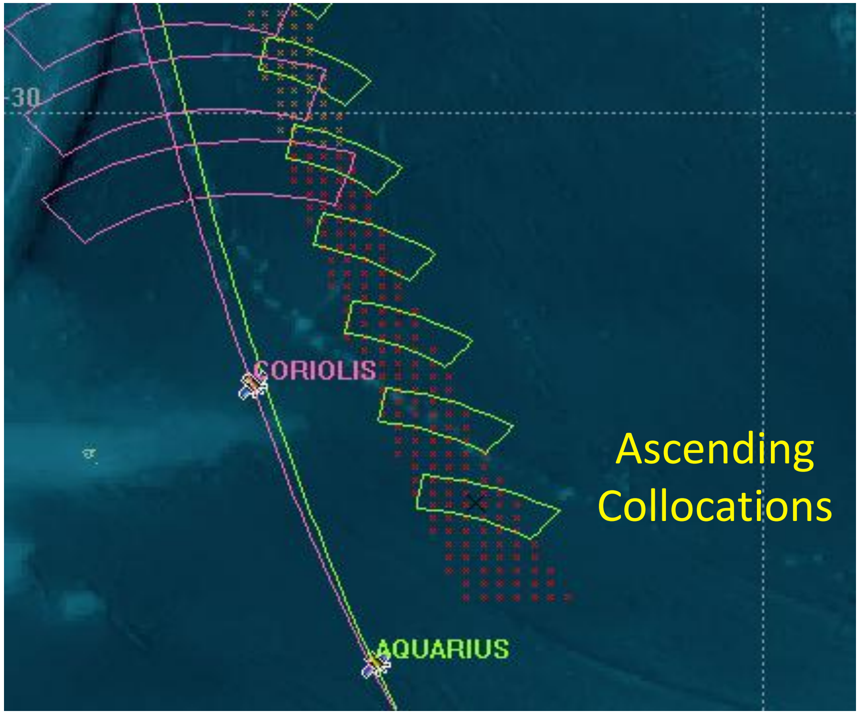

AQUARIUS
rth Inertial Axes
ul 2007 04:55:40.000 Time Step: 120.00 sec
Educational Use Only

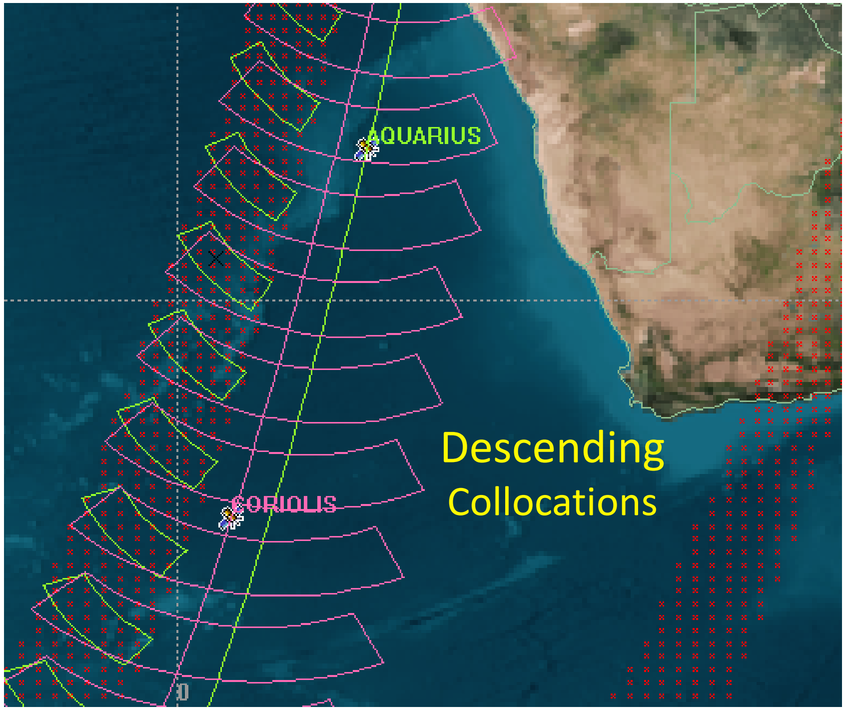


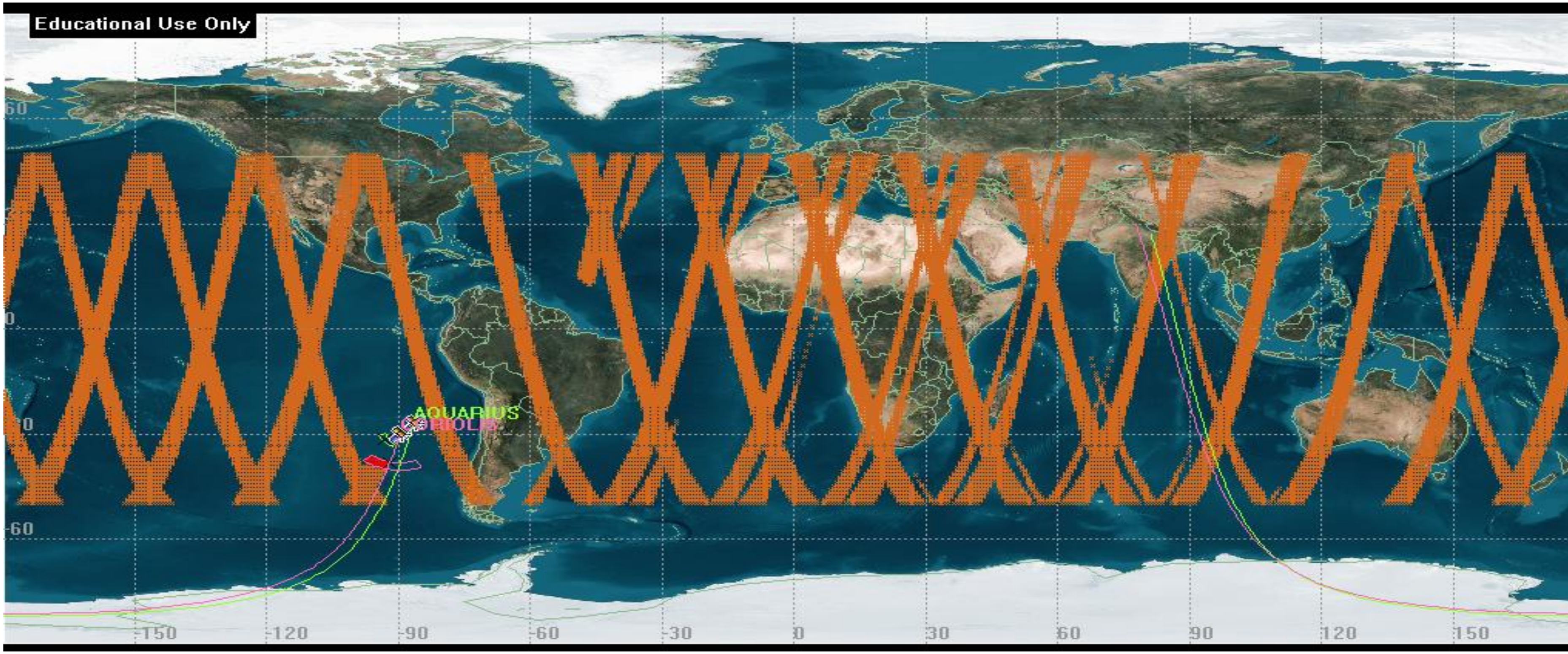


- Aquarius speed > Coriolis & it laps in ~45 hours and 36 mins
- During half of this period, satellite ground tracks are out of phase
- Time for satellite ground tracks to be coincident (in phase at same Lat/Lng) is ~57 days

ASC/DSC Collocations (0.5° resolution)







- Approx 19,000 collocations in 45 hrs (± 50^o Lat)
  - (0.5^o x 0.5^o) & ± 45 min window
- Approx 1 Million ocean collocations in 5 months

Conclusions

- The MWR T_b simulation is validated to have radiometric and temporal/spatial accuracy
- CONAE's yaw steering technique to collocate the forward & aft MWR beams has also been verified with a mean collocation separation ~ 4 Km
- The inter-satellite swath collocation between WindSat and MWR shows that ~5 months in orbit, there will be ~1 Million ocean collocations

Future Work

- A four month simulated T_b dataset for the 3-channel MWR will be delivered to CONAE for the pre-launch geophysical retrieval algorithms development
- The MWR retrievals will be validated through near simultaneous, collocated comparisons with WindSat's Environmental Data Records (EDRs)

Backup Slides

Satellite/Sensor Geometry - Incidence Plane [cont]

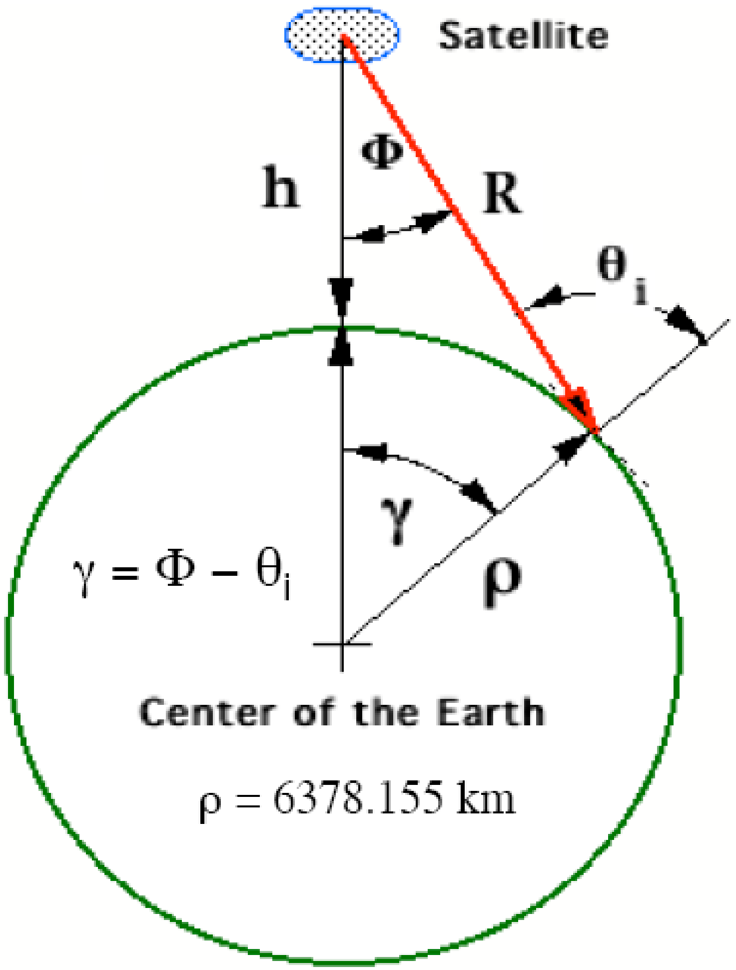
NADIR/INCIDENCE ANGLE RELATIONSHIPS

Nadir angle $\Phi = \mathrm{ASIN}\left[\frac{\rho}{\rho + h}\,\mathrm{SIN}\theta_i\right]$

Incidence Angle $\theta_i = \mathrm{ASIN}\left[\frac{\rho + h}{\rho}\,\mathrm{SIN}\Phi\right]$

SLANT RANGE

$$R = \frac{\rho\,\mathrm{SIN}\gamma}{\mathrm{SIN}\Phi}$$

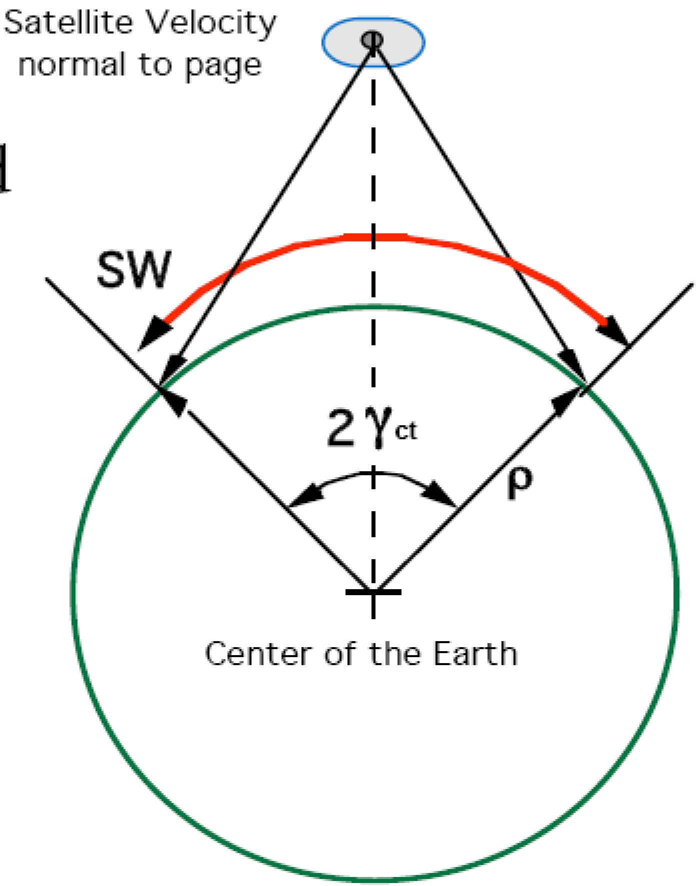


Satellite/Sensor Geometry - Across-Track Plane

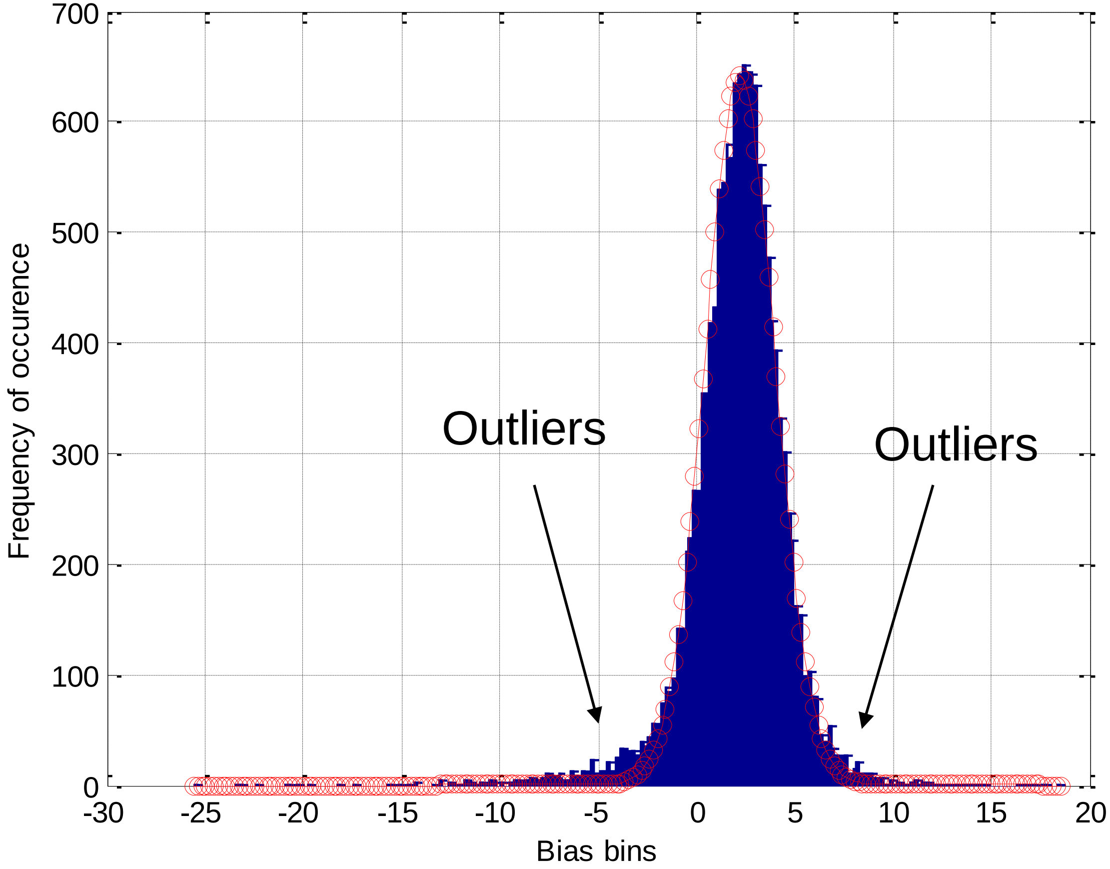
Swath Width is measured in the cross-track plane along the surface of the earth

$$SW = 2\,\gamma_{ct}\,\rho$$

Note: γ_{ct} is in units of radians



Best-Fit Gaussian



Gaussian fit for Bin # 5 of Wind Speed Bias