

Terrestrial Hydrology Program Proposal Tasks

Global Surface Water Mission Design Constraints from ICESat & Streamflow Data Analysis



How often must river discharge be estimated?

analyze in-situ stream gauge data for representative U.S. rivers to assess discharge retrieval accuracy as a function of basin size and sampling frequency, assuming measurement of discharge is perfect

based on common basin characteristics, apply above retrieval accuracies globally to assess accuracy of continental and global water budget estimation

How often can rivers be observed by an orbital laser altimeter?

assess ICESat's altimeter channel frequency of observing the Earth surface with sufficient signal strength, as a function of season, time of day, laser energy, and atmospheric transmissivity
(i.e. a 1064 nm laser climatology)

assess ICESat's return energy from inland water surfaces, as a function of off-nadir pointing angle, laser energy, and atmospheric transmissivity

Jasinski & Stoll Tasks

Harding & Carabajal Tasks

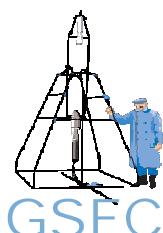
How accurately can river discharge be estimated by orbital laser altimetry?

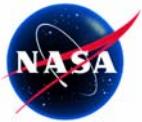
establish how accurately ICESat can measure open inland water stage and slope by comparison to gauged rivers, lakes, and reservoirs

establish how accurately ICESat can measure vegetation-covered inland water stage and slope by comparison to gauged wetlands

perform hydrologic modeling of selected river reaches, using the above estimates of stage and slope retrieval accuracy as inputs, to establish the controlling factors on discharge estimation accuracy

define design constraints for future laser altimeter mission observations of water storage and discharge



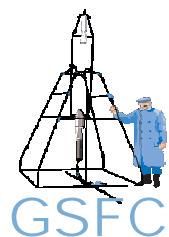


Laser Altimeter Mission Design Constraints from ICESat Observations of 1064 nm Apparent Surface Reflectance

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NASA Goddard Space Flight Center – Code 698

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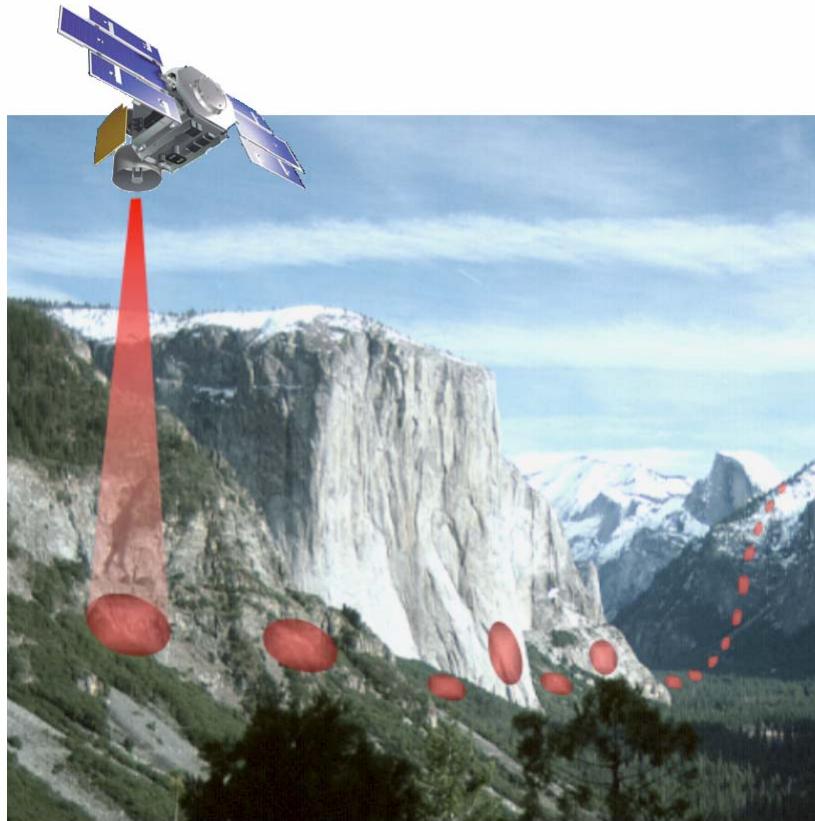


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Laser Altimeter Design Constraint: Apparent Reflectance



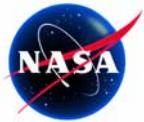
A laser altimeter's probability of detecting a return from the surface, and the accuracy of the resulting range measurement, depends on the received signal strength.

Signal strength depends on the surface's apparent reflectance, which is the product of the surface retro-reflectance and two way atmospheric transmission =

$$R_{\text{surface}} * \tau^2_{\text{atm}}$$

The ICESat mission provides comprehensive, global data on 1064 nm apparent reflectance useful for designing future laser altimeter mission implementations, such as the ICESat-II, DESDynI and LIST missions recommended in the NRC Earth Science Decadal Survey.





ICESat Apparent Reflectance



ICESat operates several times a year in ~month long periods (grey vertical bars). Transmit energy from the three lasers used in sequence (L1, L2, L3) decreases through time.

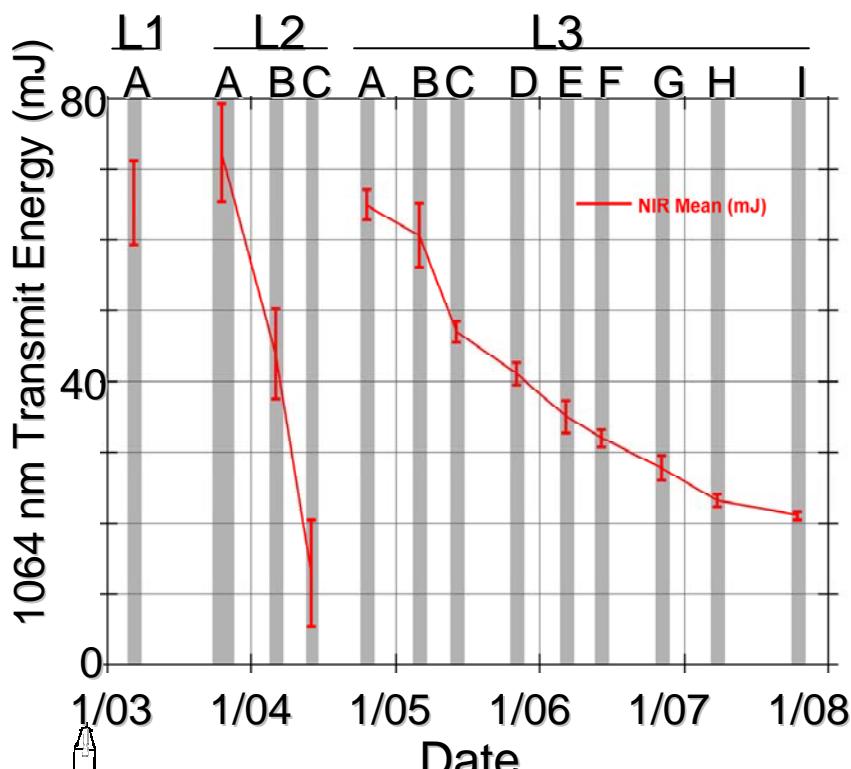


Figure courtesy of C. Shuman



$$\text{Apparent Reflectance} = \frac{\text{Received Energy}}{\text{Transmit Energy}}$$

assuming Lambertian scattering from surface and accounting for orbit altitude

Normalizes changes in transmit energy within and between observation periods

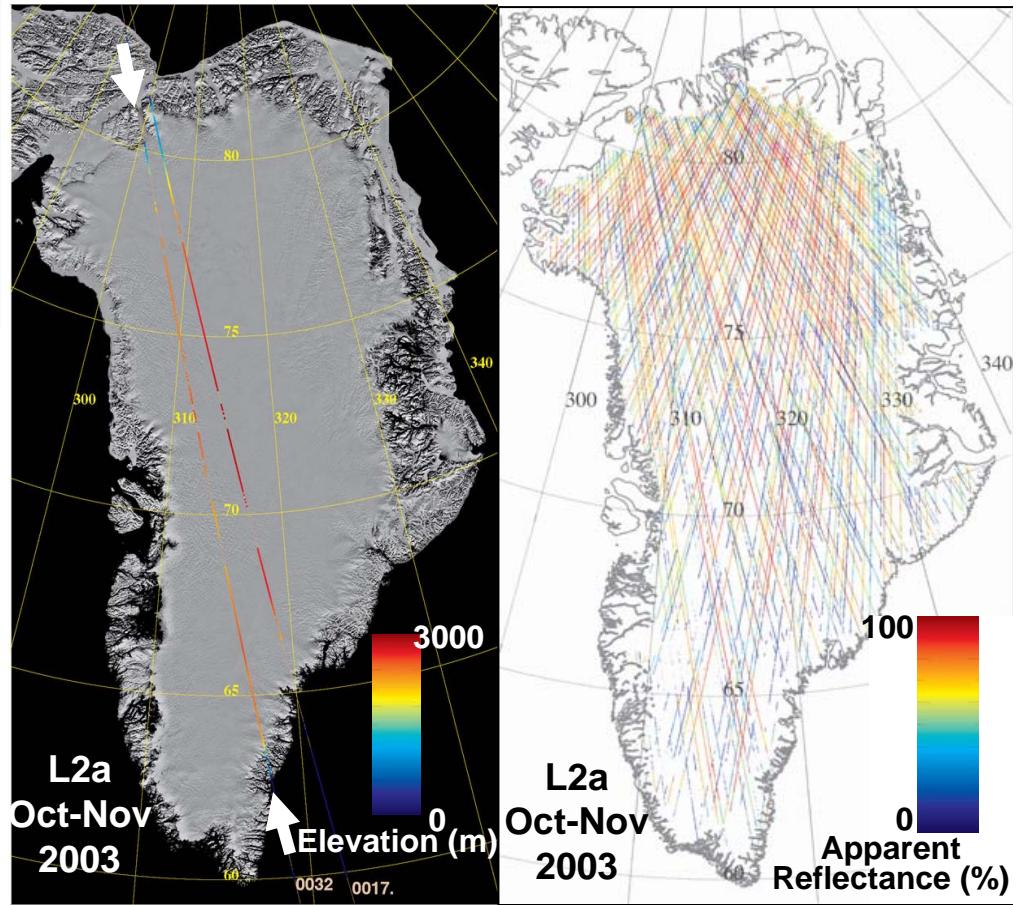
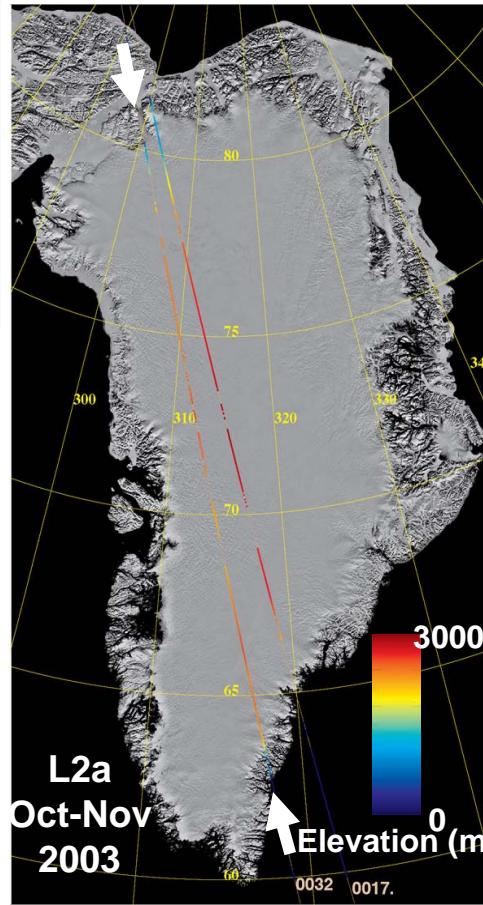
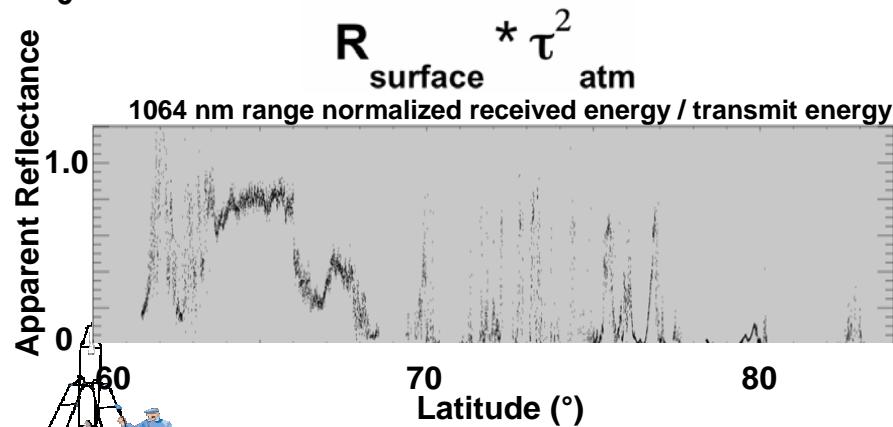
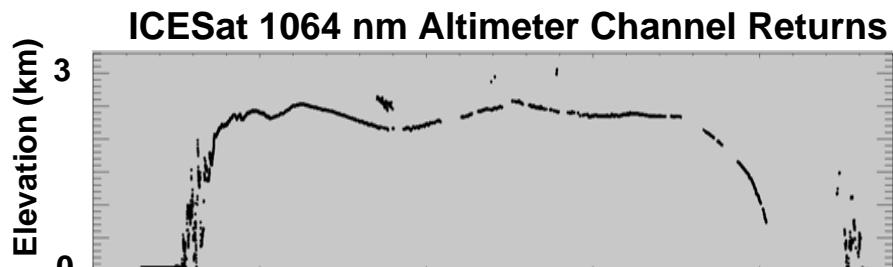
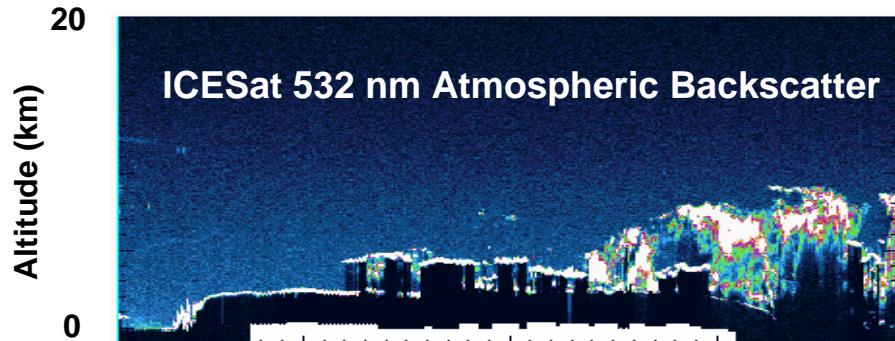
Result can be >100% because laser altimeters observe retro-reflectance "hot-spot" with parallel illumination and view angles (0° phase angle)



Apparent Reflectance = $R_{\text{surface}} * \tau^2_{\text{atm}}$



Apparent reflectance is highly variable in space and time, primarily due to variability of atmospheric transmission, a function of the optical depth of clouds and aerosols, and surface retro-reflectance.



$$\text{Apparent Reflectance} = \frac{\text{Received Energy}}{\text{Transmit Energy}}$$

Assuming Lambertian scattering from surface and accounting for orbit altitude.
Normalizes changes in transmit energy within and between observation periods.

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ICESat-1 Predicted Performance vs. Apparent Reflectance

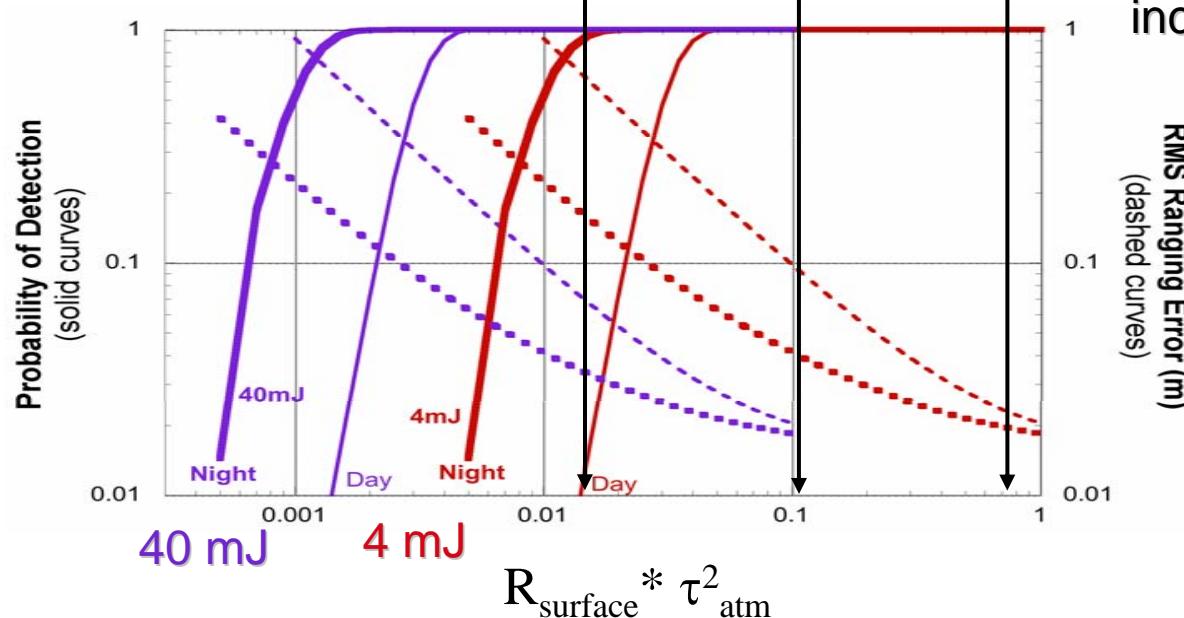
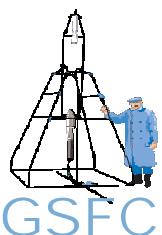


Apparent Reflectance provides the basis to predict the probability of detecting a return from the Earth's surface and the resulting ranging precision. These model results by Xiaoli Sun are for the GLAS instrument transmitting 40 mJ and 4 mJ per NIR pulse and ranging to a flat surface sloping 3 degrees.

	moderate	thin	none
Cloud cover:			
Optical depth:	2.0	1.0	0.1
1-way transmission:	14%	37%	90%
Ice sheet app. refl.:	1.5%	10%	70%
Detection probability:	100%	100%	100%
Day time range error:	10 cm	2 cm	2 cm
Night time range error:	4 cm	2 cm	2 cm

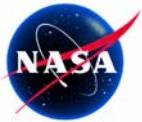
No forward scattering effect included

ICESat designed to range to ice sheets through thin to moderate cloud cover (optical depth ≤ 2) yielding apparent reflectance of 1%



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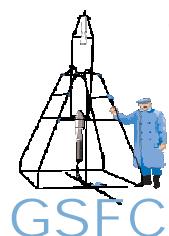
Analysis Goals



- o Establish frequencies of ICESat return types:
 - Successful ranges to the Earth's surface
 - Ranges to cloud top
 - No return detected due to cloud absorption &/or scattering
- o For surface returns, establish distributions for 1064 nm apparent surface reflectance
 - (Correcting instrumental effects on apparent reflectance)
- o Evaluate seasonal & annual variations for regions with different atmospheric and land cover characteristics

Polar Ice Sheet:

Interior East Antarctica
Coastal East Antarctica
West Antarctic Ice Streams
Ice Stream E
Flood Range
Greenland



Mid-latitude Land (L2a):

Amazon Basin
Mid-Atlantic U.S.
SW U.S.

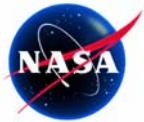


Apparent Reflectance Corrections Applied



- o **Saturation energy correction (X. Sun et al.)**
 - Derived from pre-launch lab calibration data
 - Corrects for waveform distortion due to receiver saturation
- o **Detector non-linearity correction (X. Sun et al.)**
 - Derived from pre-launch lab calibration data
 - Corrects for non-linear response of detector to received and transmit energy
- o **Receiver FOV Shadowing correction (Spinhirne et al.)**
 - Derived from on-orbit atmosphere column and ocean surface data
 - Corrects for transmit pulse to receiver boresight misalignment
- o **Absolute calibration correction (Spinhirne et al.)**
 - Derived from ocean data and SW U.S. field campaign in-situ measurements
- o **Edited data with Waveform begin offsets > 22.9 m**
 - (compression implementation error caused error in energy calculation → incorrect reflectance; will be implemented correctly in Release 429)



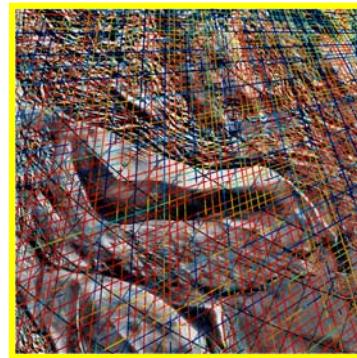


Polar Regions - Antarctica

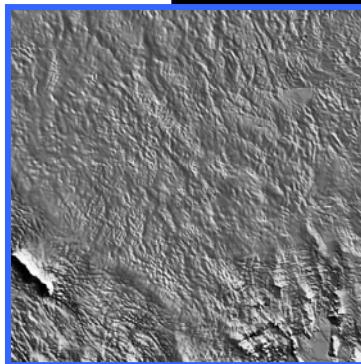


Apparent Reflectance

1.2



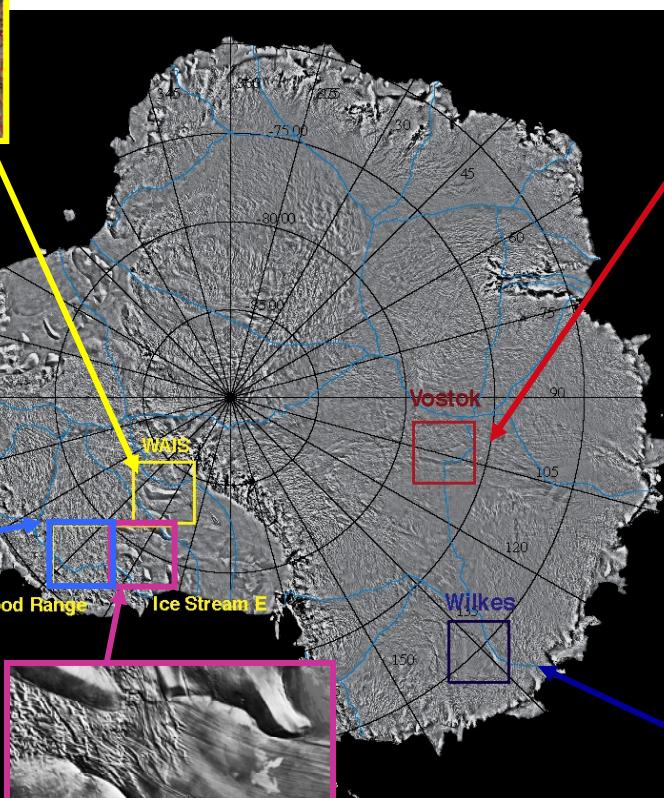
West Antarctic
Ice Streams
(WAIS)



Flood Range

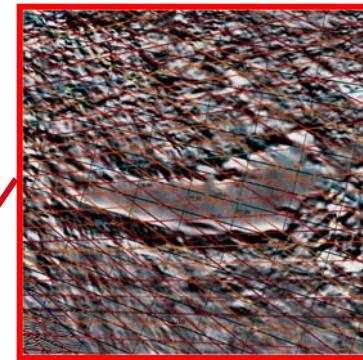


GSFC

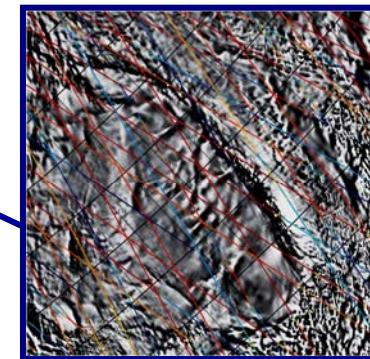


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Vostok

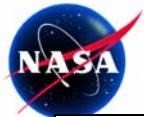


Coastal East
Antarctica



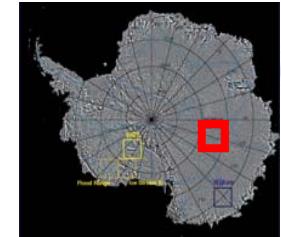
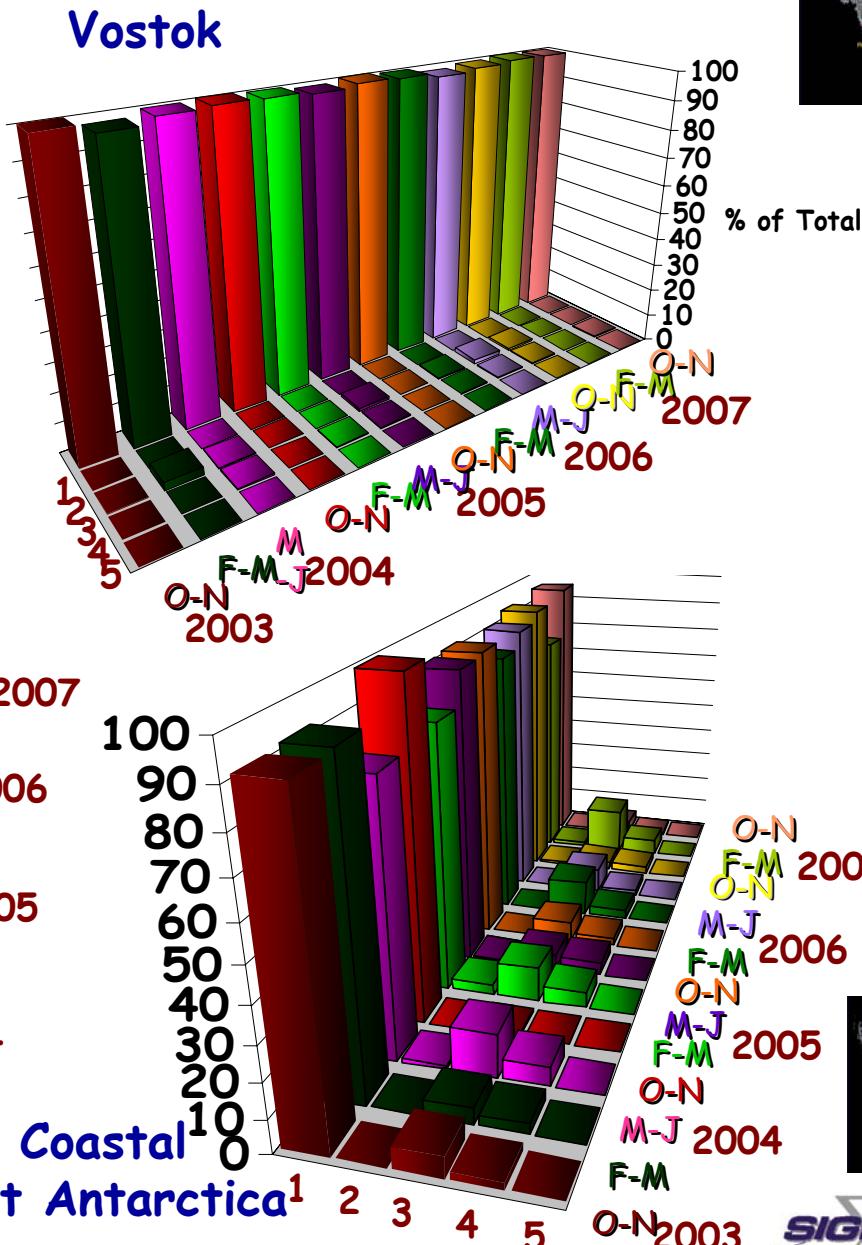
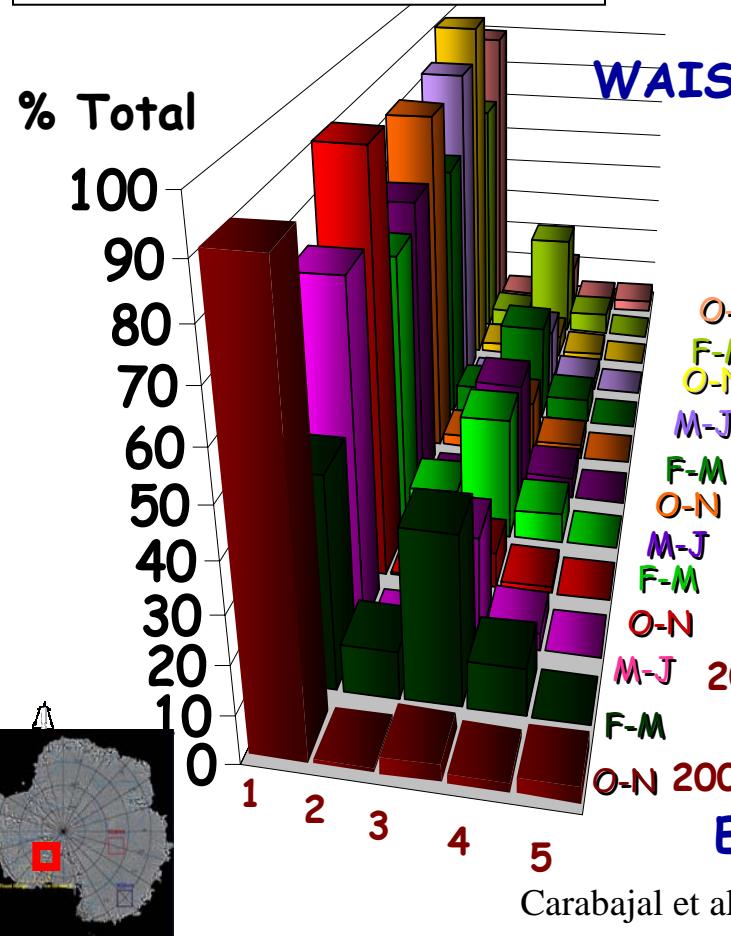
Ice Stream E



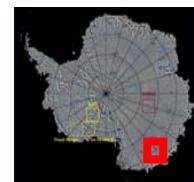


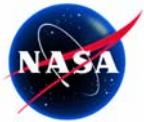
Antarctica Frequency of Occurrence

Return Type Classification	
1-	Surface return with reflectance defined
2-	Cloud top return
3-	No return
4-	Surface return with undefined reflectance
5-	Not classifiable



- L2a
- L2b
- L2c
- L3a
- L3b
- L3c
- L3d
- L3e
- L3f
- L3g
- L3h
- L3i



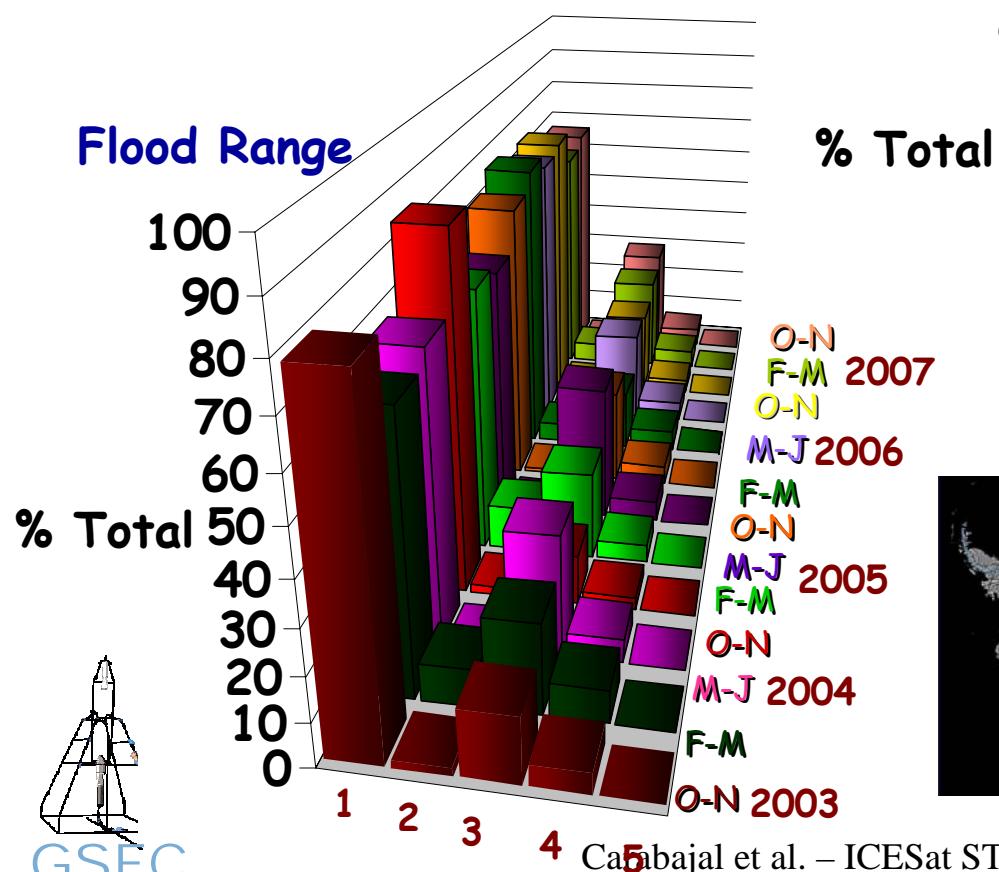
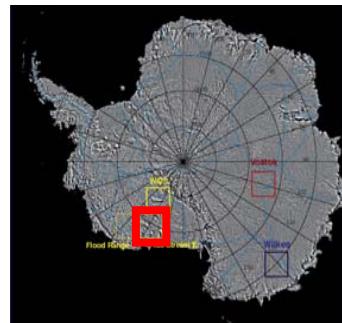


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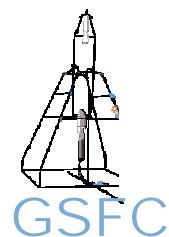
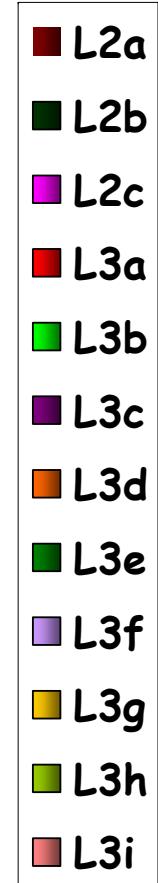
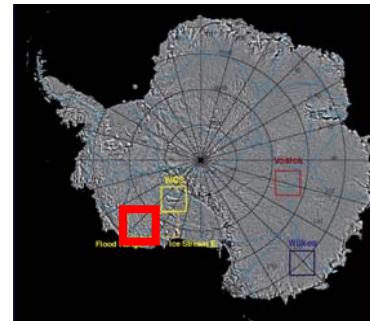
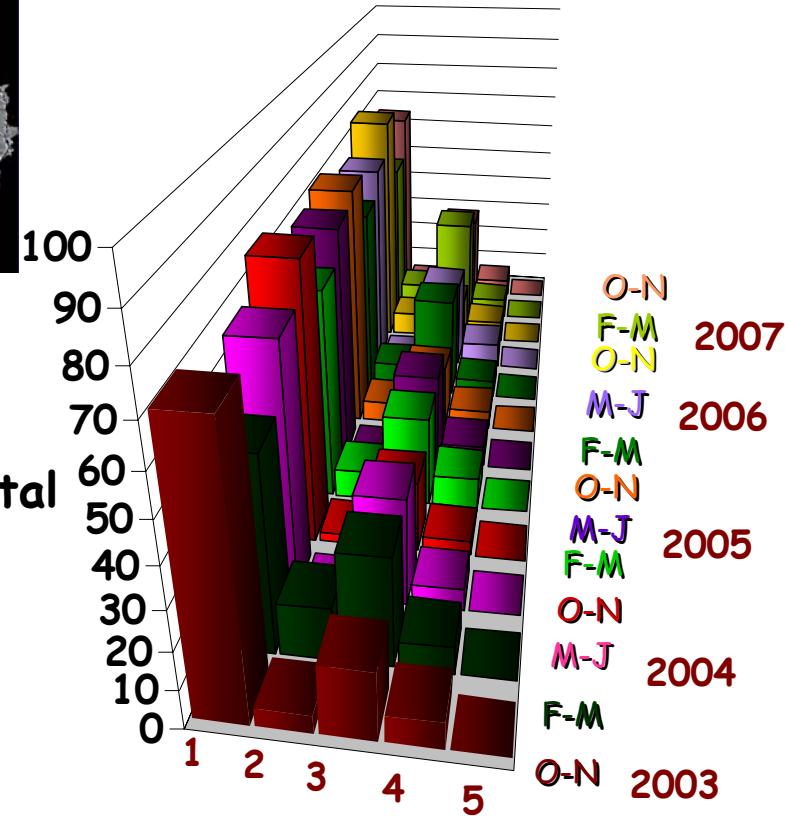


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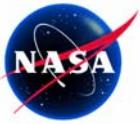


Ice Stream E



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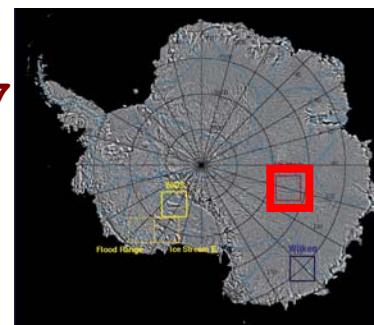
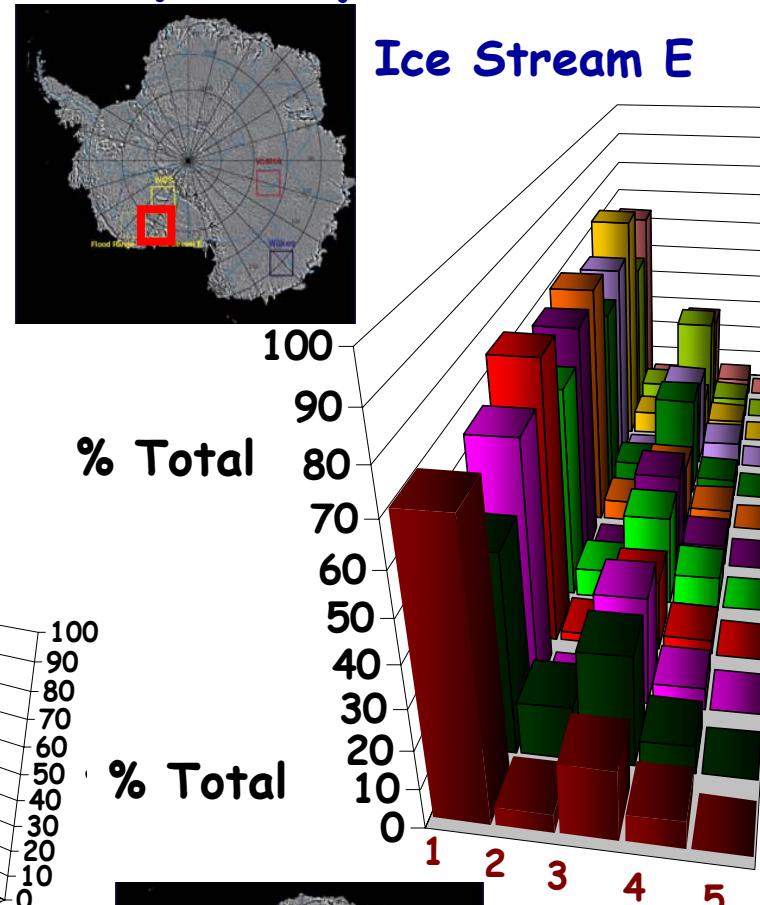
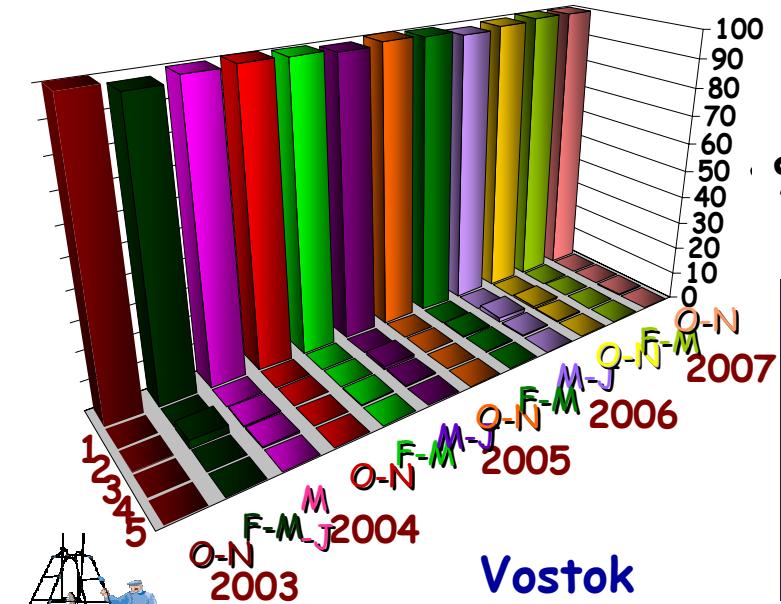


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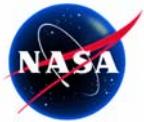
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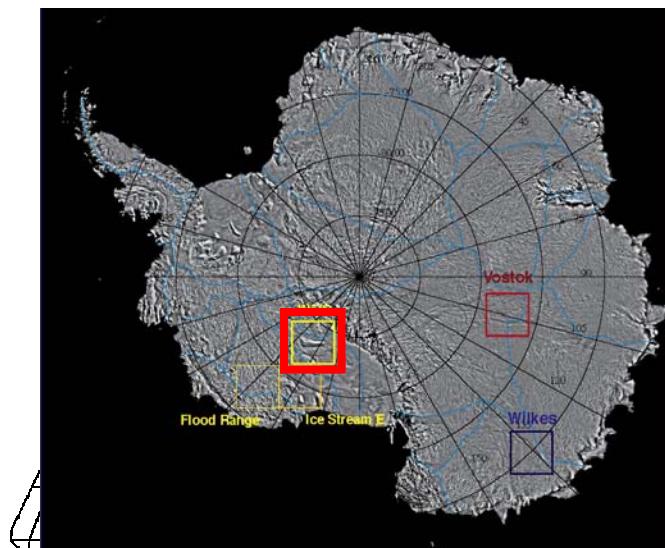
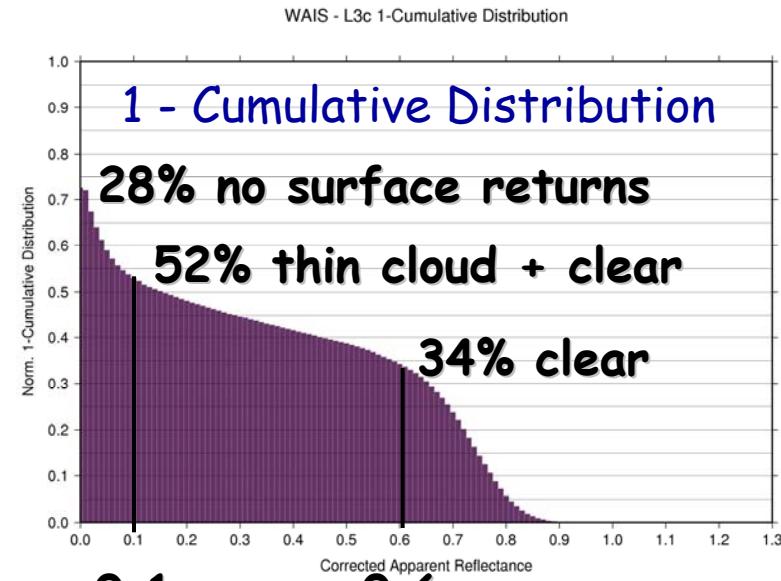
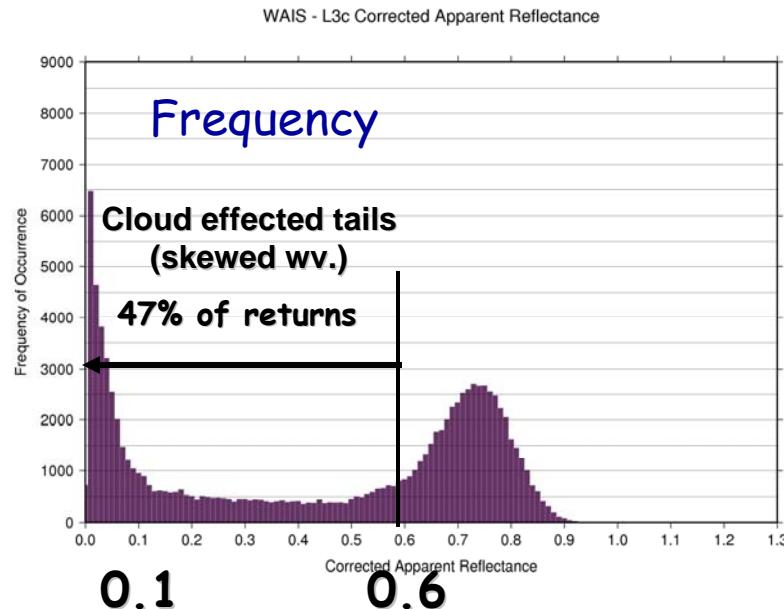


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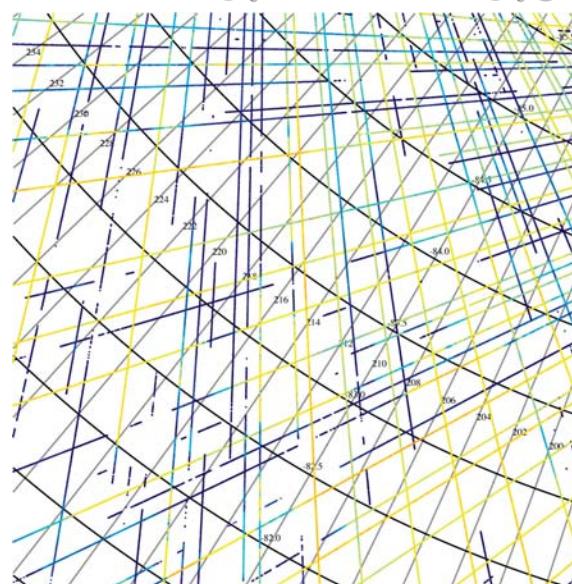


WAIS L3c (May-June 2005) Corrected Apparent Reflectance

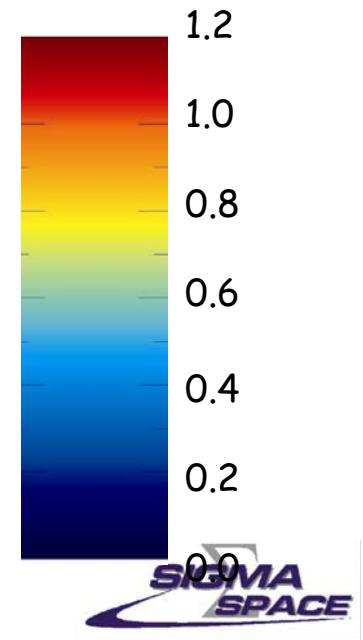


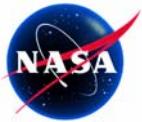
GSFC

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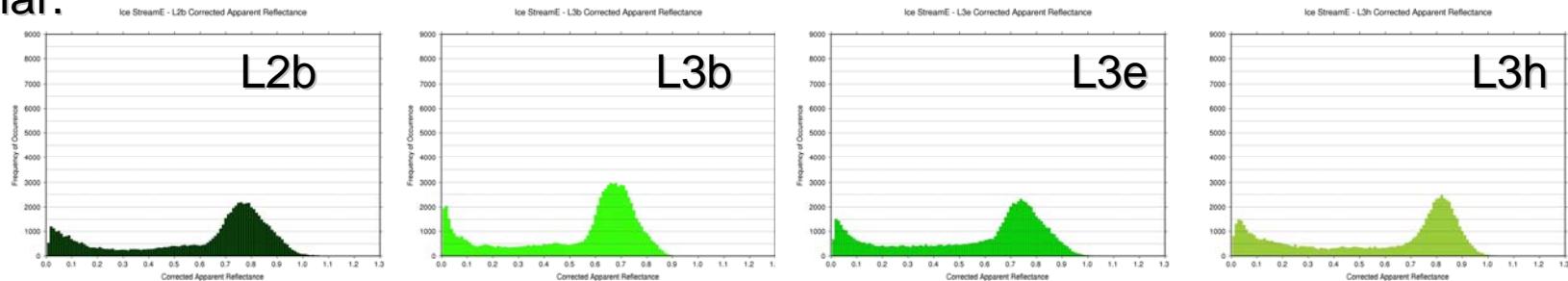
Corrected Reflectance



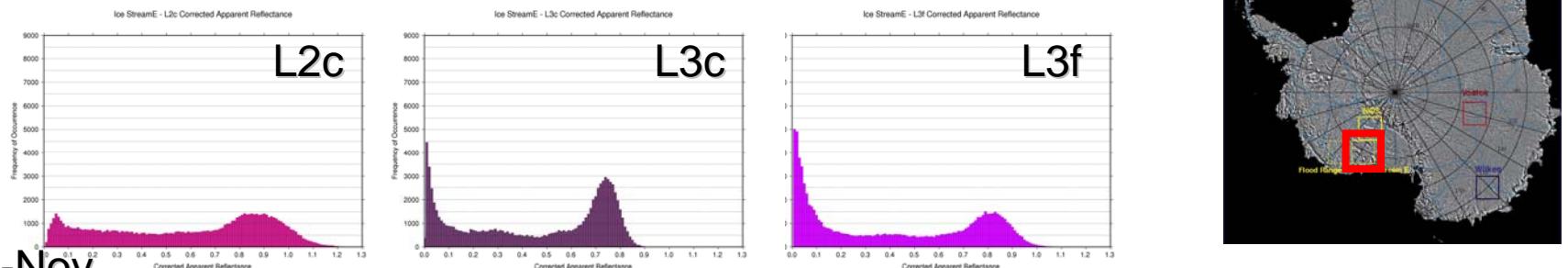


Ice Stream E - Histograms

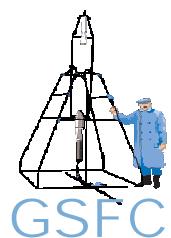
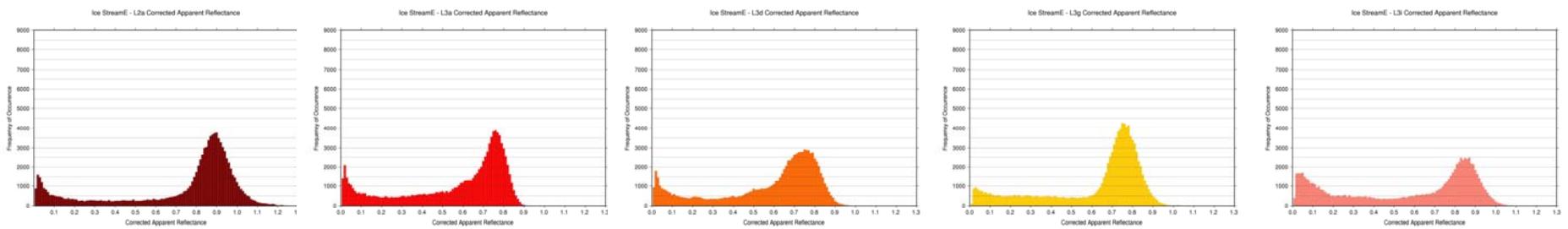
Feb.-Mar.



May-June

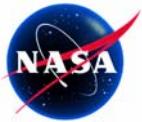


Oct.-Nov.



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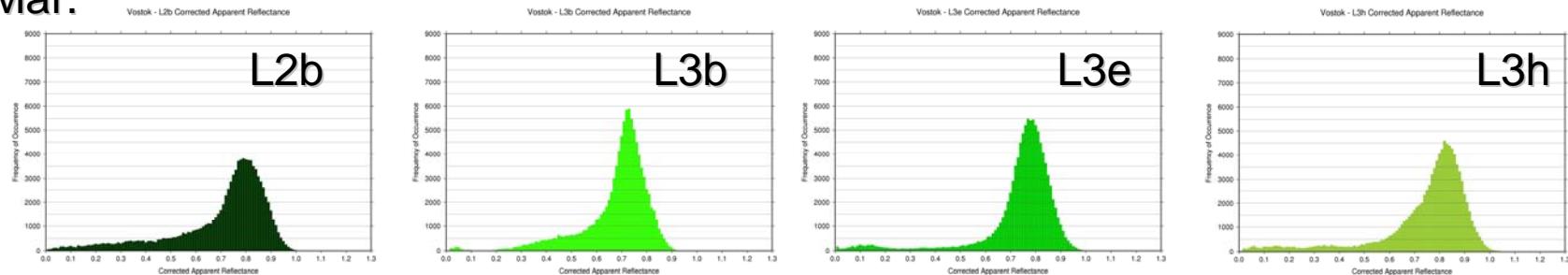




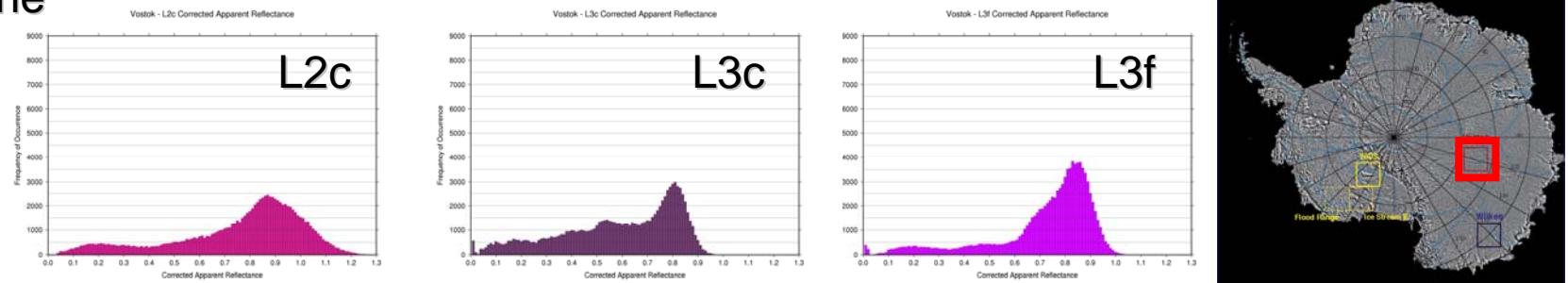
Vostok - Histograms



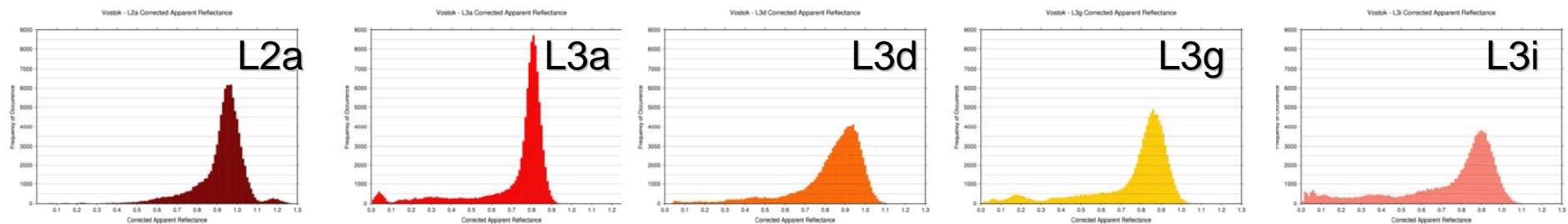
Feb.-Mar.



May-June



Oct.-Nov.



2003

2004

2005

2006

2007

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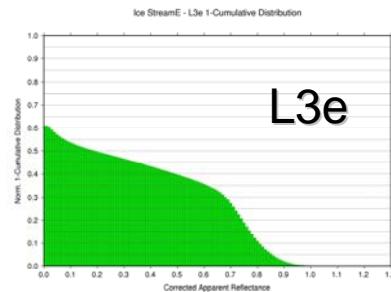
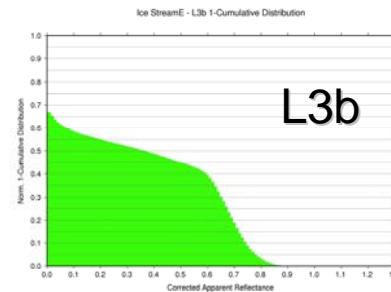
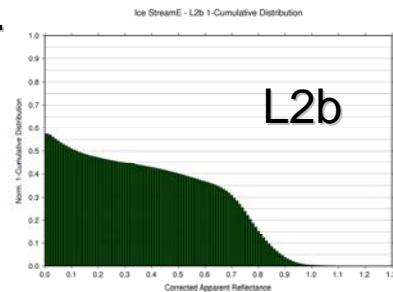




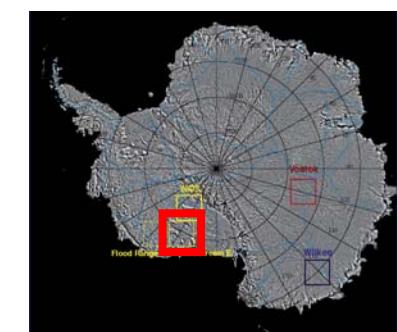
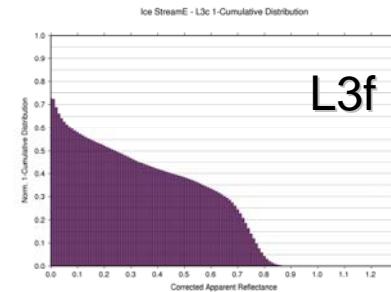
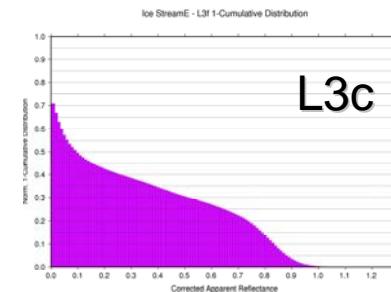
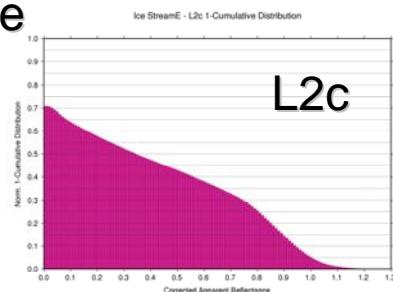
Ice Stream E 1-Cumulative Distributions



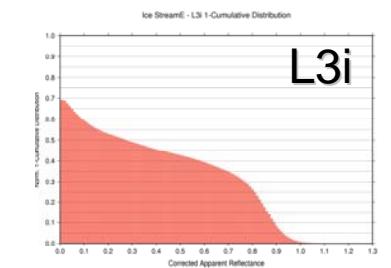
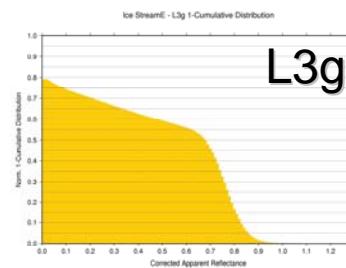
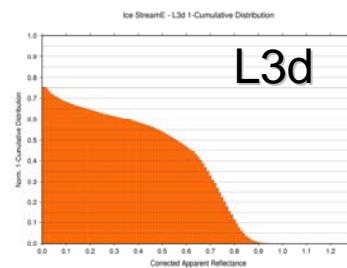
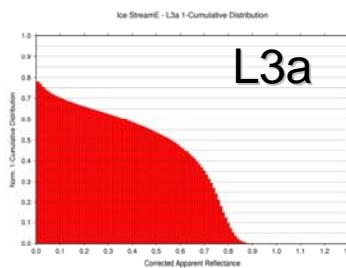
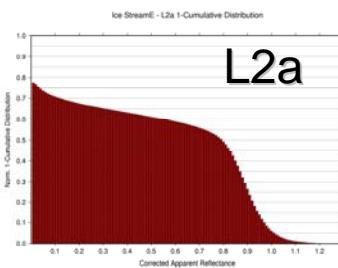
Feb.-Mar.



May-June



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2004

2005

2006

2007

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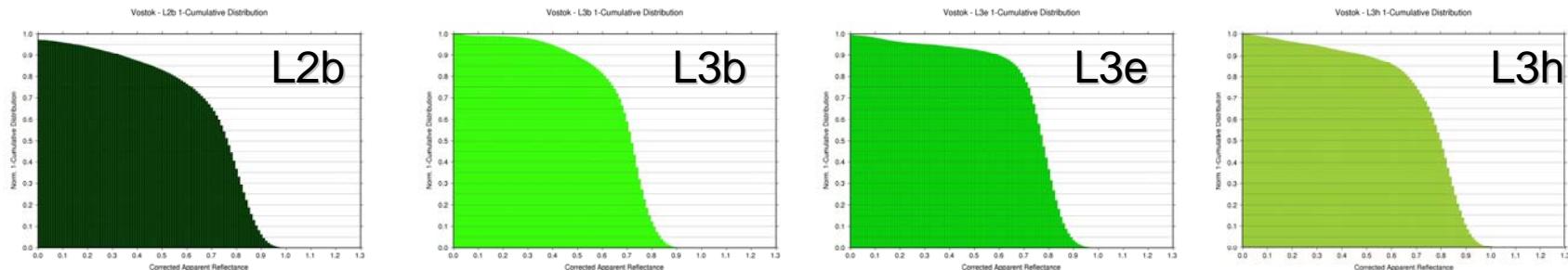




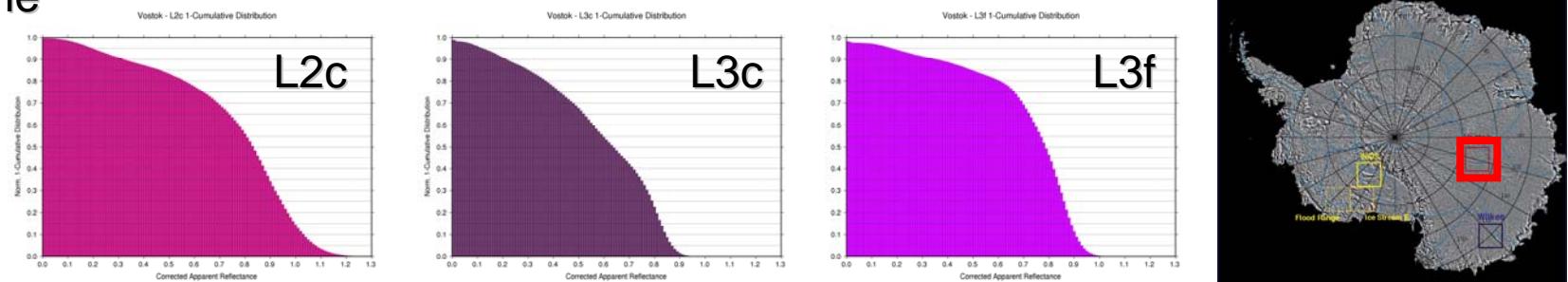
Vostok - 1-Cumulative Distributions



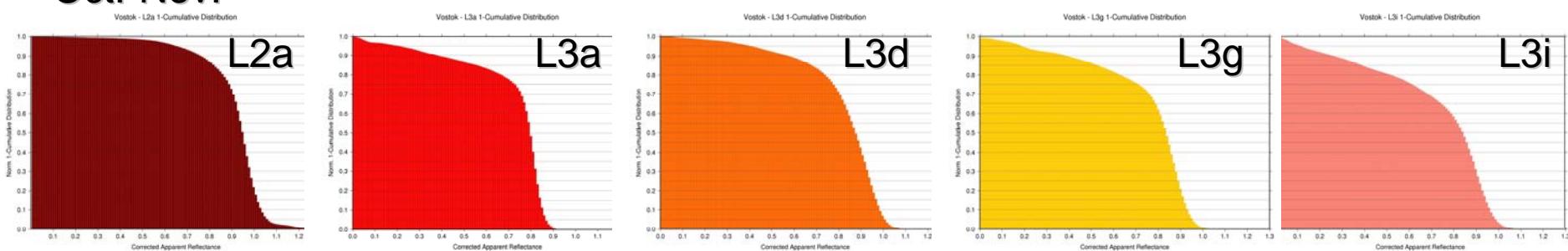
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2003

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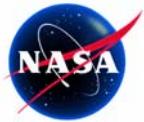
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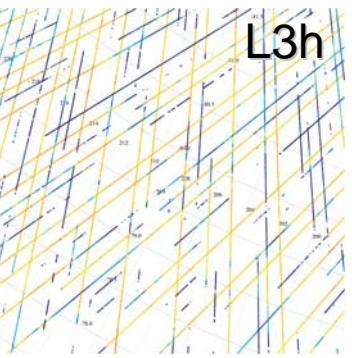
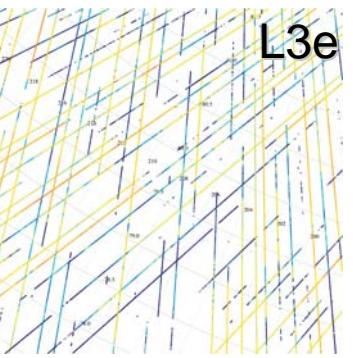
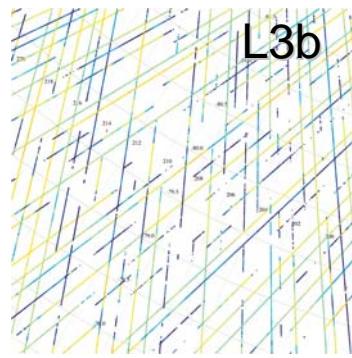
Ice Stream E - Maps



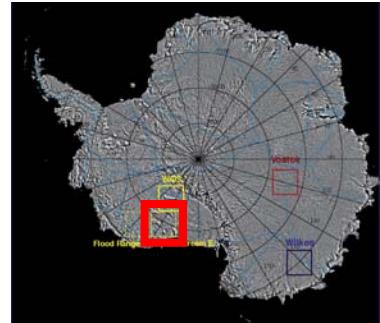
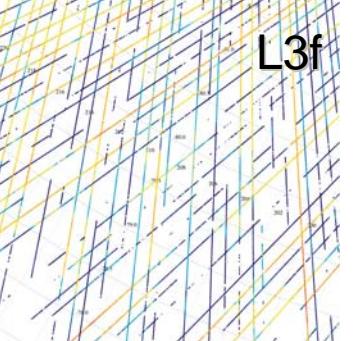
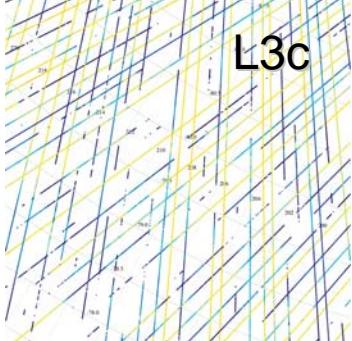
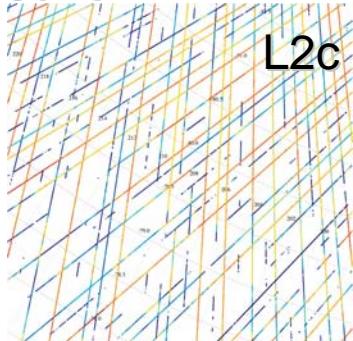
Corrected Reflectance



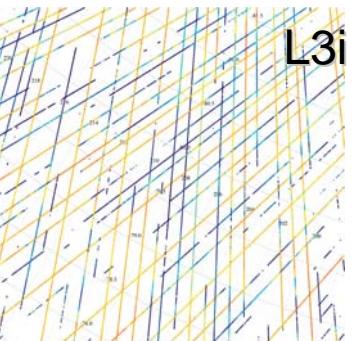
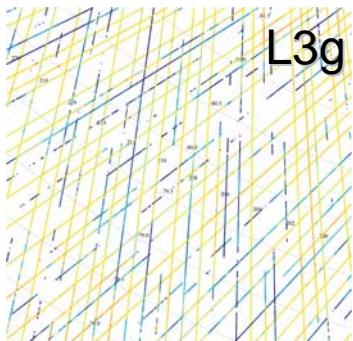
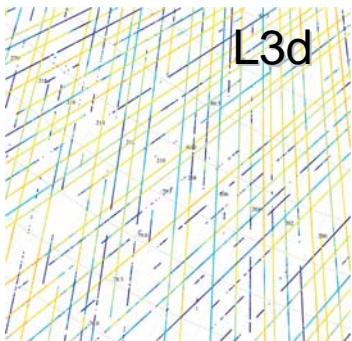
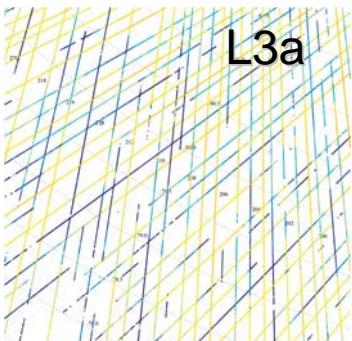
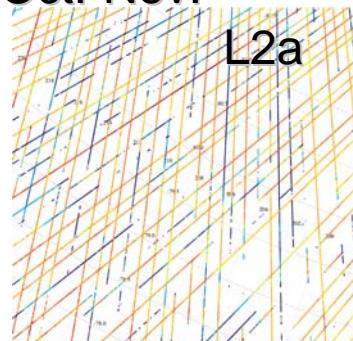
Feb.-Mar.



May-June



Oct.-Nov.



2003

2004

2005

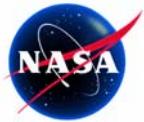
2006

2007



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Vostok - Maps

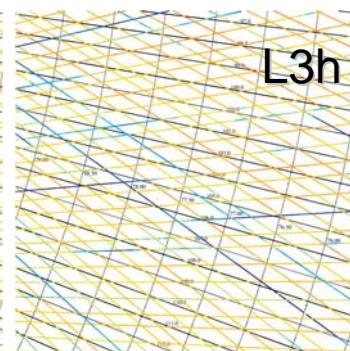
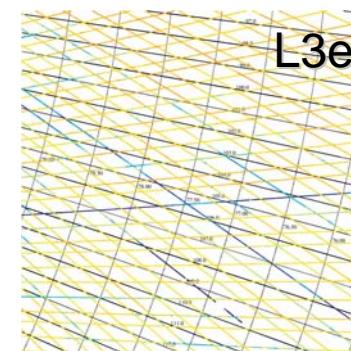
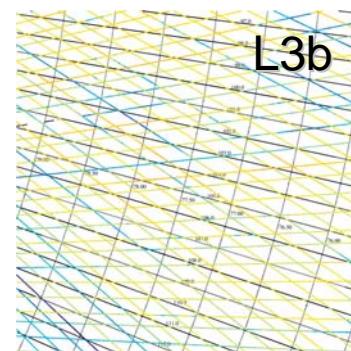
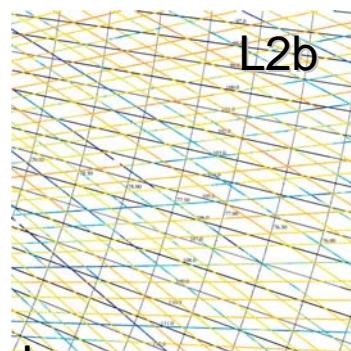


Corrected Reflectance

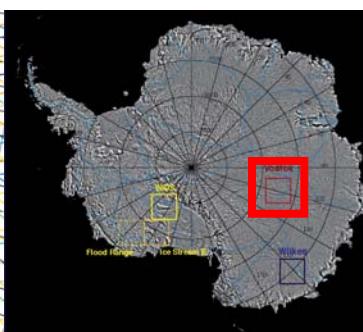
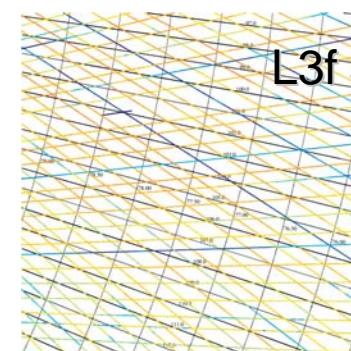
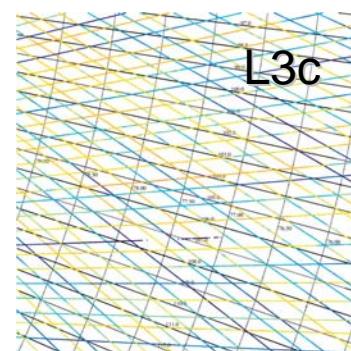
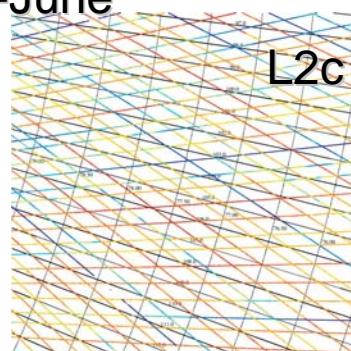
Feb.-Mar.



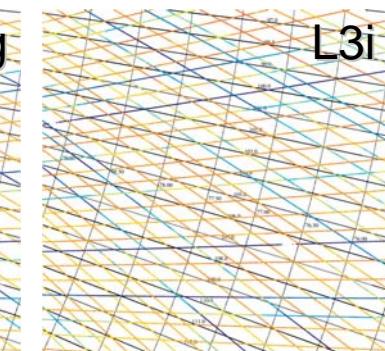
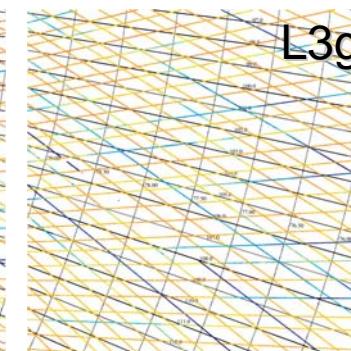
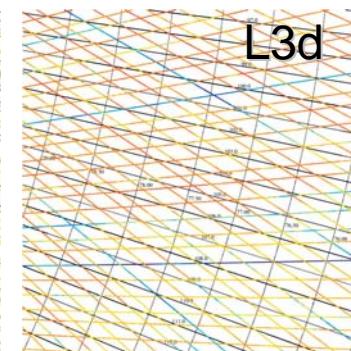
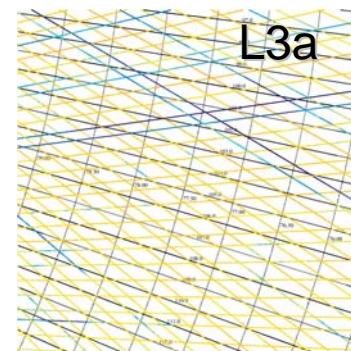
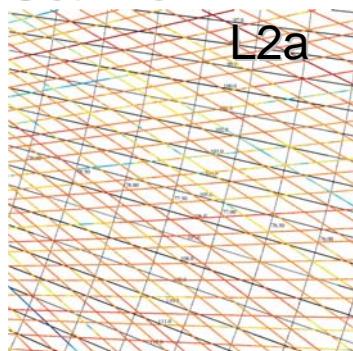
1.2
1.0
0.8
0.6
0.4
0.2
0.0



May-June



Oct.-Nov.



2003

2004

2005

2006

2007

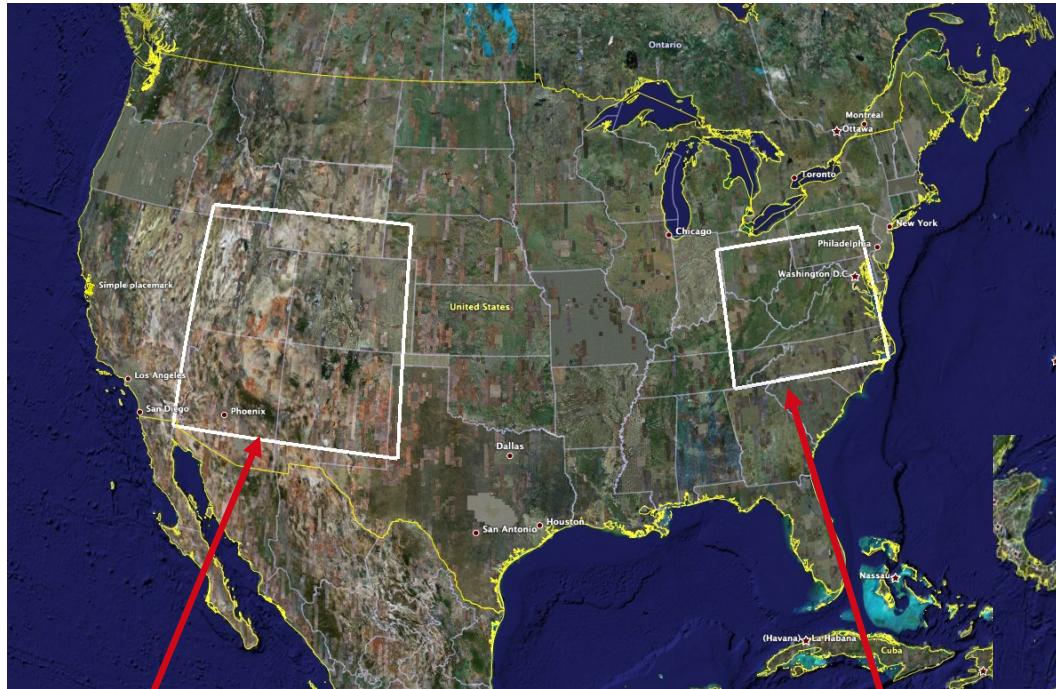


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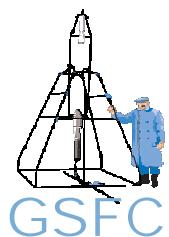
Mid-Latitude Regions - Amazon and U.S.



Western U.S.

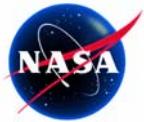
Mid-Atlantic U.S.

Amazon Basin



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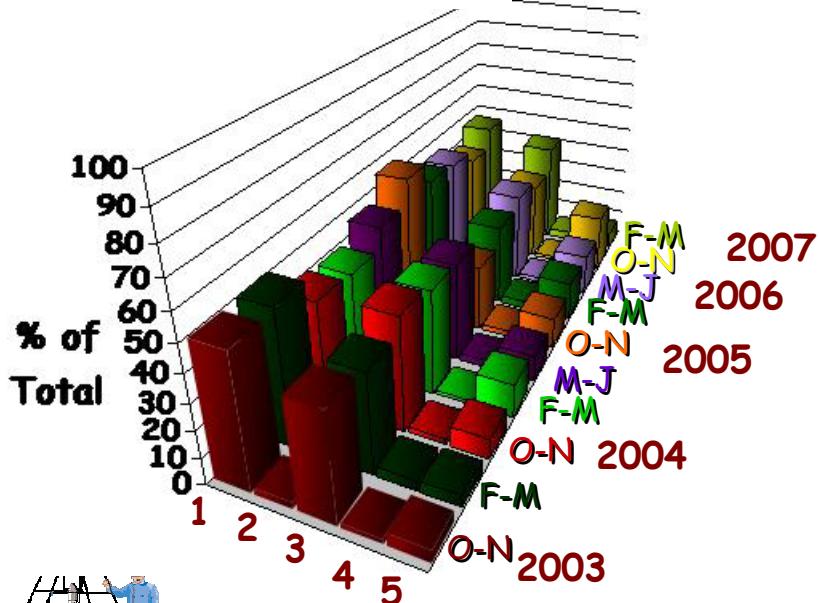
Land Areas Frequency of Occurrence



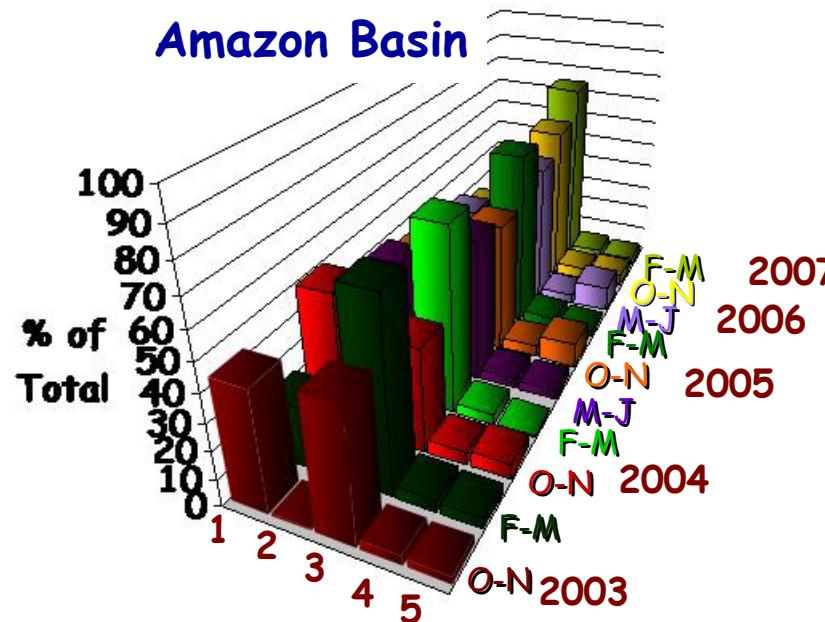
Return Type Classification

- 1- Surface return with reflectance defined
- 2- Cloud top return
- 3- No return
- 4- Surface return with undefined reflectance
- 5- Not classifiable

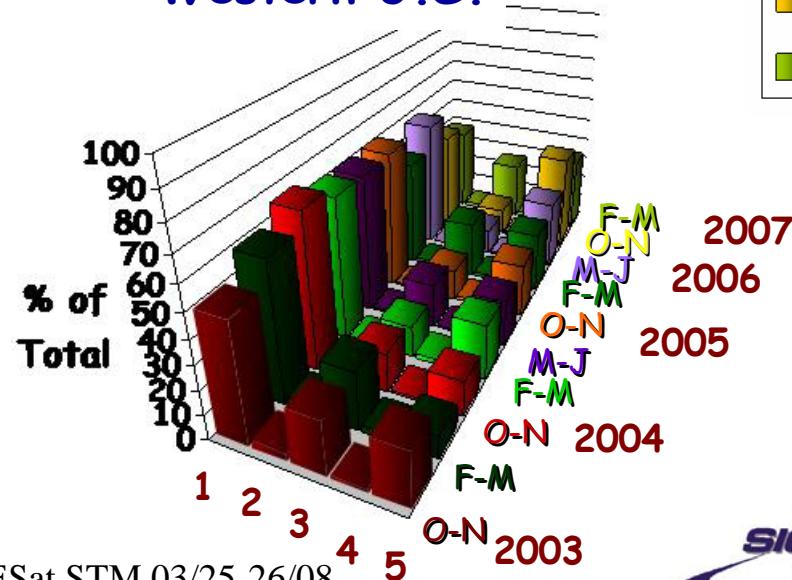
Mid-Atlantic U.S.



Amazon Basin



Western U.S.

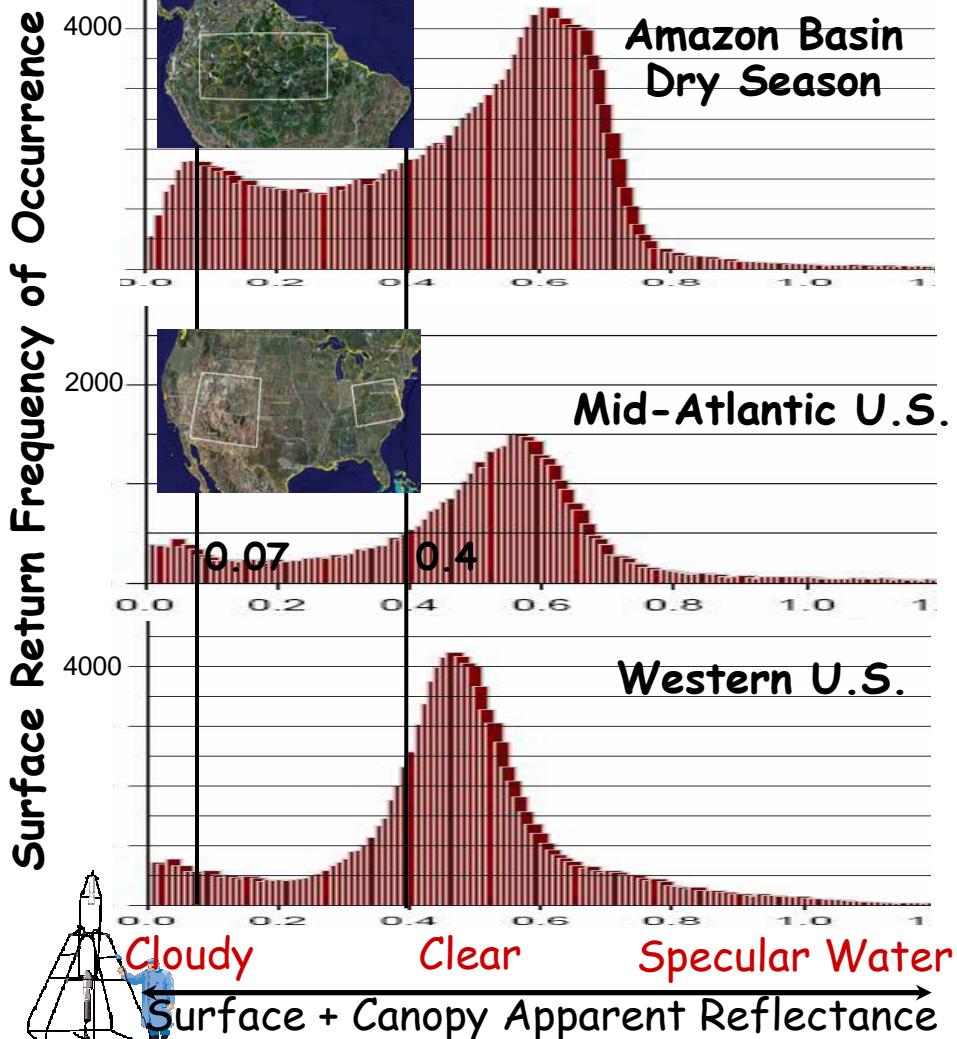




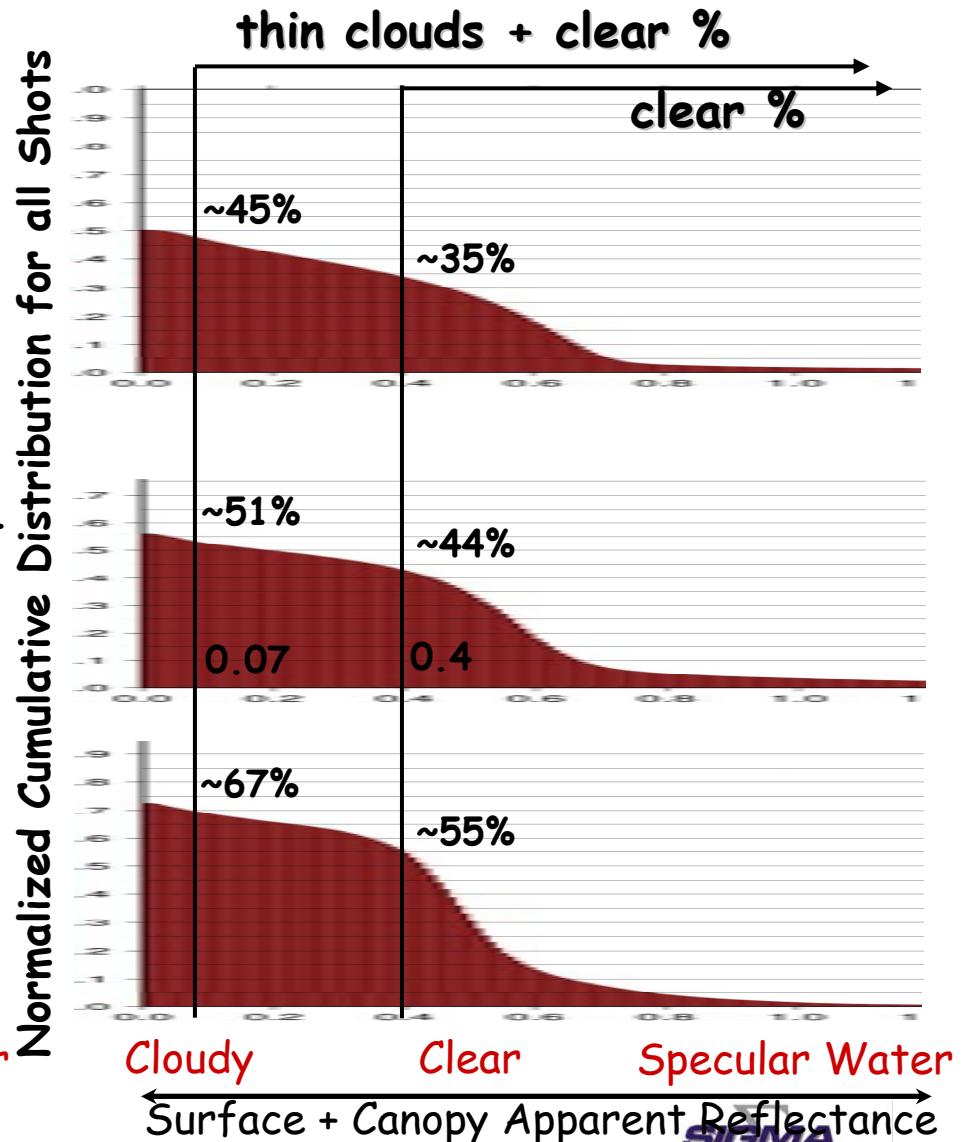
Mid-Latitude Regions Geographic Variability



Frequency Histograms



1 - Cumulative Distributions





Conclusions & Future Work



- o ICESat provides, for the first time, a means to characterize the apparent reflectance of the Earth's surface at 1064 nm, due to the combined effects of surface retro-reflectance ("hot spot" at 0° phase angle) and atmospheric transmission.
- o This information is needed to optimize the performance of future Earth orbiting laser altimeters, ensuring that sufficient probability of ranging through cloud cover is achieved.
- o Combining the predicted probability of successful ranging with the time and space sampling of a spaceflight mission scenario will enable quantitative modeling of the expected spatial coverage and density of laser returns acquired through time.

Areas of future work include:

- o Examination of diurnal variations, made possible because ICESat samples throughout the day in a non-sun-synch orbit.
- o Creation of global maps that characterize seasonal and diurnal variations of frequency of ICESat surface returns and apparent reflectance distributions.

