Submillimeter-wave Remote Sensing of Cirrus Anvils during CRYSTAL-FACE

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Bill Smith, Dan Zhou, and Paolo Antonelli for NAST-I data

Background

1) Submillimeter radiometry is a new technique for remote sensing cloud ice water path (IWP) and median mass equivalent sphere particle diameter (D_{me}).
2) Theoretical studies have shown that submillimeter brightness temperature depressions due to scattering by cirrus are more directly related to IWP than visible, infrared, or radar data.
3) Modeling has shown that multifrequency submillimeter radiometers should be able to retrieve accurate IWP and D_{me} for IWP>10 g/m^2, D_{me}>75 μm, and T<-30 C.

- Two submillimeter radiometers (FIRSC and CoSSIR) operated during the CRYSTAL-FACE experiment in Florida in July 2002, providing the opportunity to demonstrate and validate this new cirrus remote sensing technique with the wealth of data available.

Far-Infrared Sensor for Cirrus (FIRSC)

- Developed at NASA Langley by Mike Vanek and Ira Nolt
- Fourier Transform Spectrometer with a polarizing beam splitter
- Cryogenically cooled bolometer detector (0.3 K)
- Current spectral range: 15 to 50 cm^{-1} (450 to 1500 GHz)
- Spectral resolution: 0.2 cm^{-1}; FTS scan time: 4 sec
- NEΔT: > 1.1 K at 45 cm^{-1} (increases as $1/\nu^2$ for lower wavenumbers)
- Nadir viewing with 1.7° beamwidth
- Operates autonomously on Proteus aircraft since December 2000

FIRSC Performance during CRYSTAL-FACE

- FIRSC operated successfully during 7 Proteus flights.
- FIRSC didn't operate during 5 flights; some loss of data on others.
- Interferometer mirror position sampling errors caused the noise to be much higher than anticipated. Odd FTS scans were much noisier than even scans, so only even scans are used in the analysis.

Conically Scanning Submillimeter-wave Imaging Radiometer (CoSSIR)

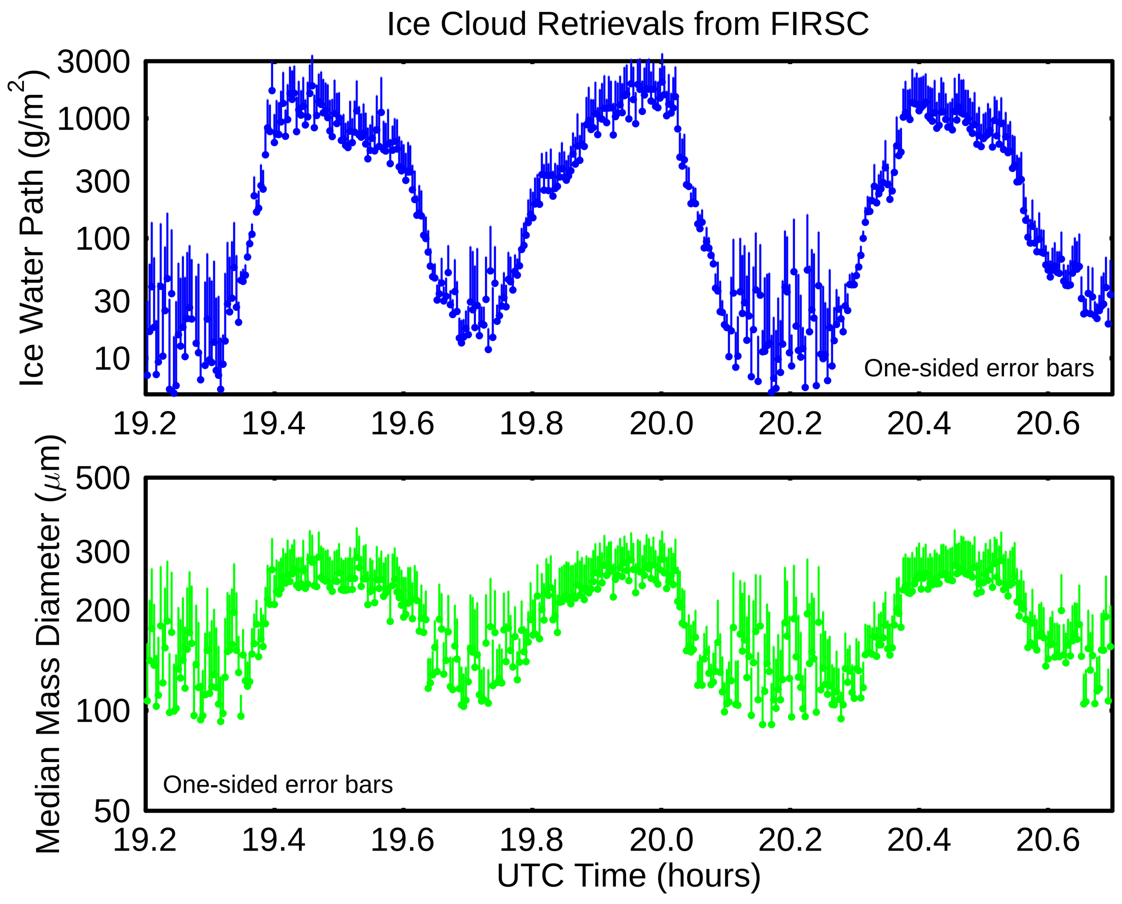
- Developed at NASA Goddard by Paul Racette and Jim Wang
- Heterodyne radiometer with receivers at 183, 220, 380, 487, 640 GHz
- 12 double sideband channels: 3@183, 1@220, 4@380, 3@487, 1@640
- Two axis scanning for conical or cross-track with 4° beamwidth
- Flies in foward wingpod of ER-2
- First flew in June 2002

CoSSIR Performance during CRYSTAL-FACE

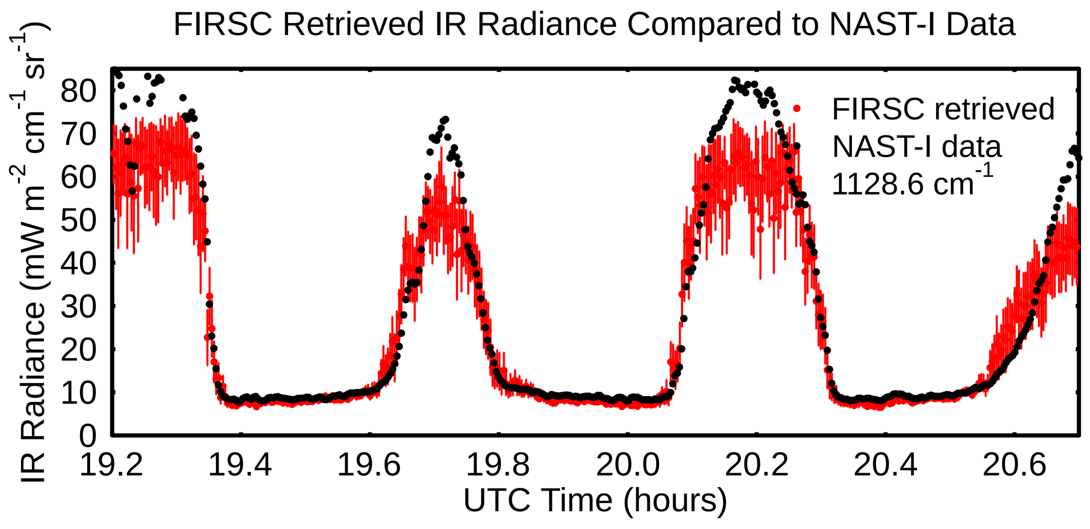
- CoSSIR operated during 7 ER-2 flights.
- CoSSIR failed on 6 flights due to motion control problem.
- 487 GHz receiver failed after transit flight to Florida.
- 380 GHz receiver had large local oscillator drift and failed after July 28.
- 183, 220, and 640 GHz receivers were stable, though 640 was noisy.

FIRSC Retrievals and Evaluation

Ice Cloud Retrievals from FIRSC

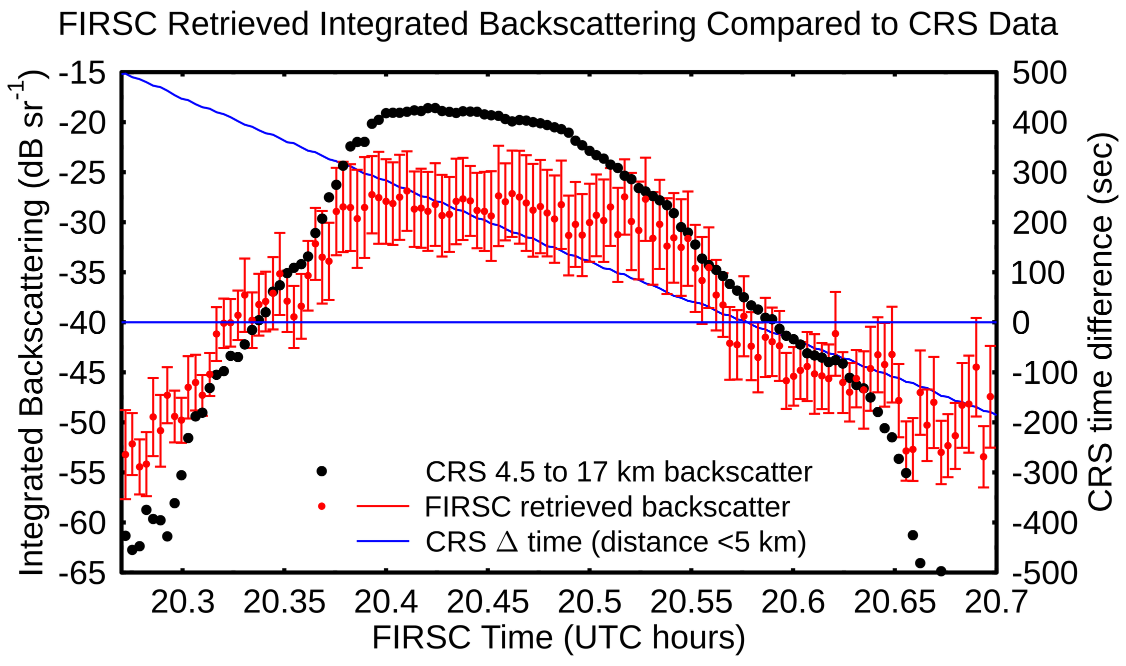


FIRSC Retrieved IR Radiance Compared to NAST-I Data



- FIRSC retrieved IR radiances agree within error bars except for clear regions where FIRSC noise gives cirrus with IWP=10-30 g/m^2.

FIRSC Retrieved Integrated Backscattering Compared to CRS Data



- During CRYSTAL-FACE there was only one Proteus - ER-2 colocation over thick anvil when FIRSC and CRS were both working.
- FIRSC retrievals agree within error bars except for thinnest regions (lack of sensitivity) and deep precipitating anvil where lower frequencies are needed to sense lower altitudes.
- FIRSC retrieved backscattering error bars are much larger than for CoSSIR retrievals due to FIRSC's high noise and lack of low frequencies.

Cirrus Retrieval and Evaluation Procedure

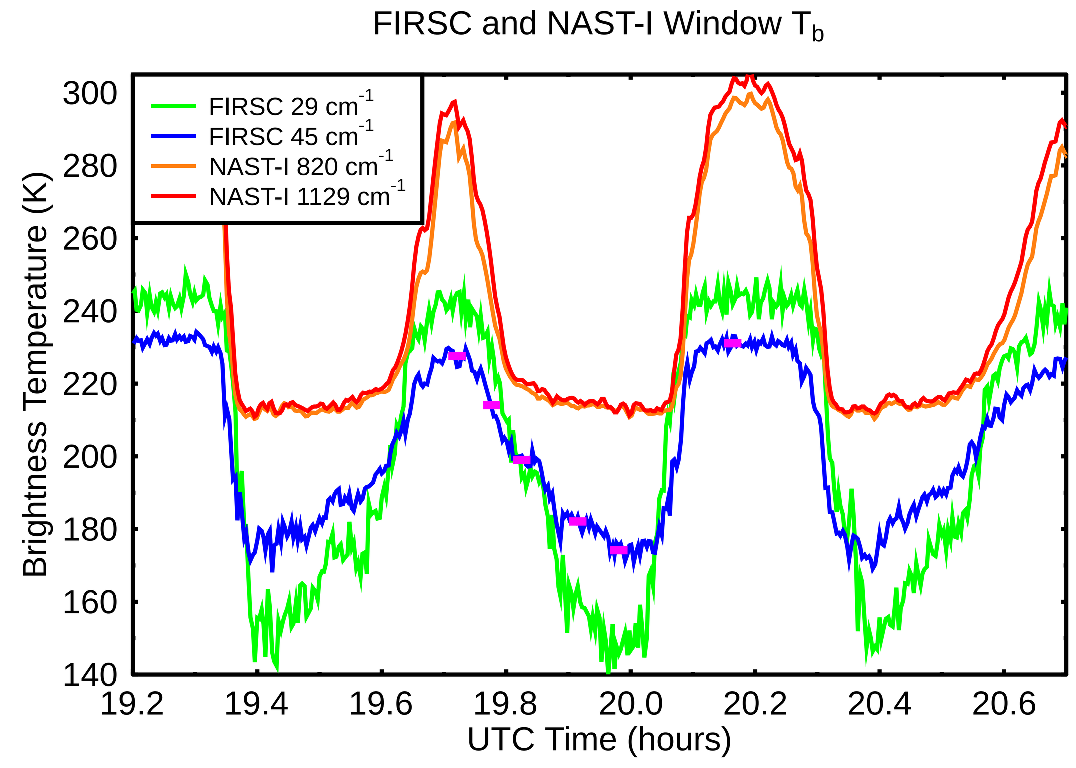
- IWP and D_{me} with 1 sigma error bars are retrieved with the Bayesian algorithm of Evans et al. (JGR, February 2002).
- Retrieval database contains 400,000 cases with random profiles/cirrus properties and associated simulated brightness temperatures.
- Statistics of temperature and relative humidity profiles are from 25 sondes.
- Statistics of cirrus top and bottom IWC/D_{me} (correlated to temperature) are from 2DC data from CEPEX. Will use CRYSTAL-FACE in situ probe microphysics in the future.
- Scattering properties for 4 and 7-bullet rosettes and ρ=0.46 g/cm^3 spheres (plus 3 types of variable density spheres for CoSSIR).
- Gaussian distribution of cloud top height (mean=12.7 km) and exponential distribution of thickness (mean=5.0 km) are derived from radar.
- FIRSC T_b spectrum is compressed into 6 principal components.
- Retrieved properties are weighted average of database cases that match observations (weighted by $e^{-\chi^2/2}$).

- We believe that evaluation of passive remote sensing retrievals should be done using other remote sensing data (with independent physics) that match the sensing volume, to avoid sampling errors of in situ cloud probes.
- The Bayesian algorithm can also retrieve microwindow IR radiances and vertically integrated 94 GHz radar backscattering to compare with NAST-I IR radiances and Cloud Radar System (CRS) 94 GHz radar reflectivity.
- NAST-I flew on Proteus with FIRSC. CRS flew on ER-2 with CoSSIR.

Examples of FIRSC Data

- All data on the poster are from July 29, the day with the best FIRSC data.
- FIRSC measures the nadir viewing T_b spectrum as a function of time.

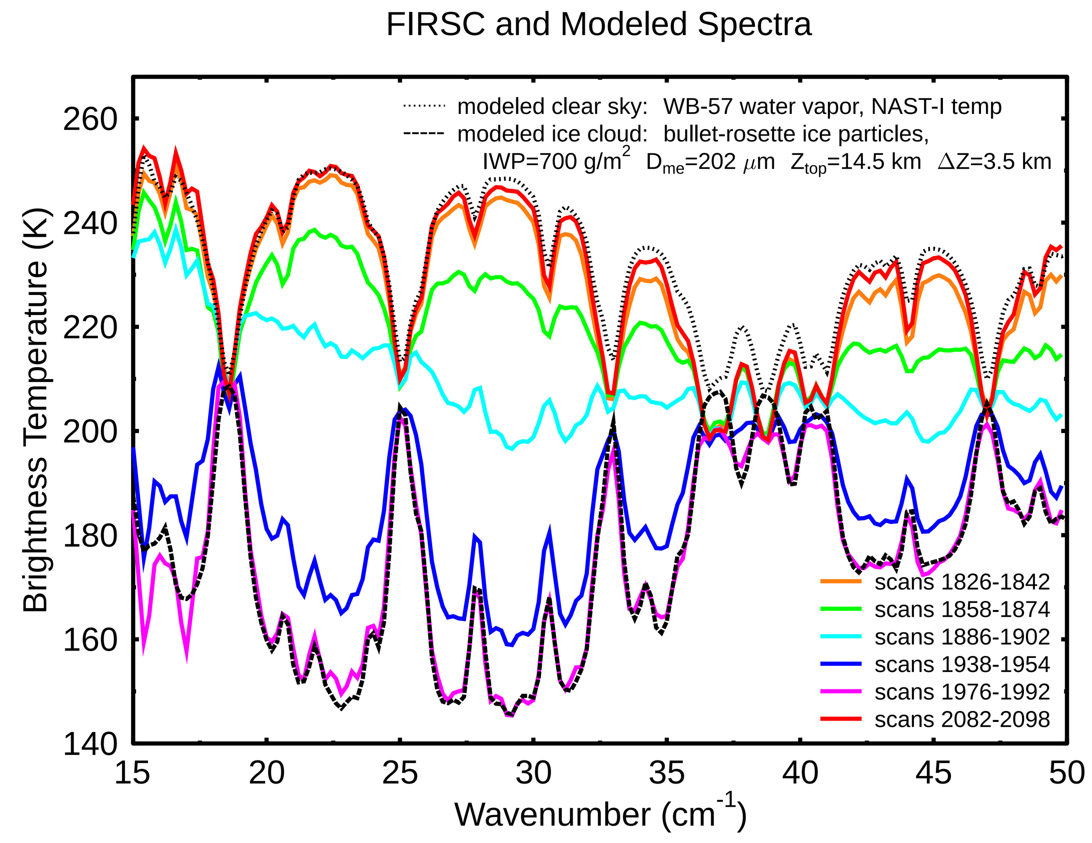
FIRSC and NAST-I Window T_b



- Submillimeter has scattering signal when IR is saturated in deep anvil.
- Measurable submm ΔT_b when IR optical depth is small at anvil edges.

Magenta bars show times of 9 scan average spectra in plot below.

FIRSC and Modeled Spectra

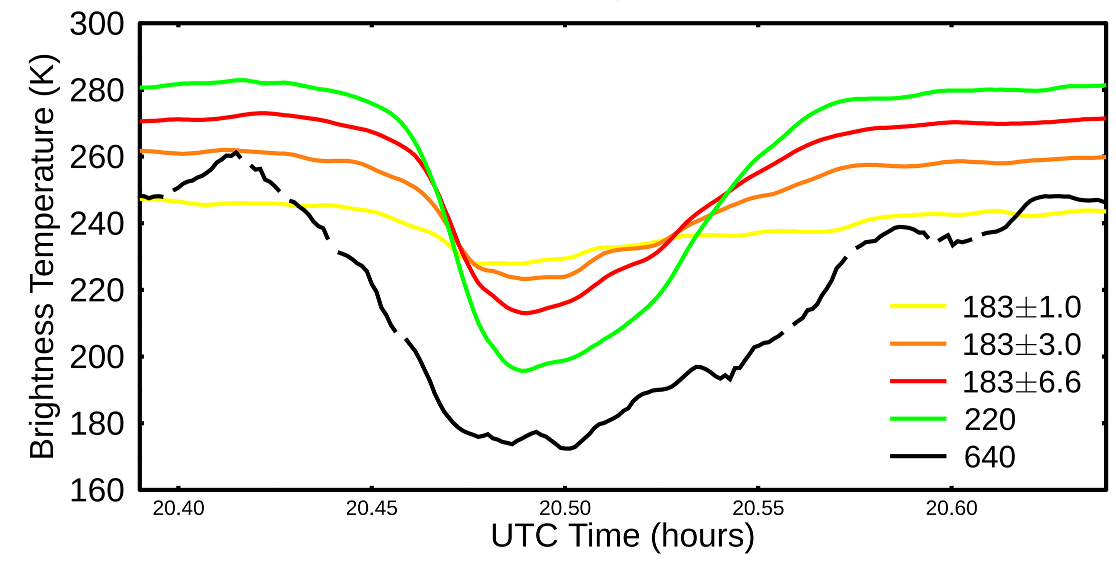


- Observed FIRSC spectra agree reasonably well with modeled clear sky and modeled ice cloud spectra (cloud parameters from eyeballl fit).
- Substantial ΔT_b in 45 cm^{-1} window for anvils with high cloud tops, though larger ΔT_b (and less water vapor absorption) at 22 and 28 cm^{-1}.

CoSSIR Retrievals and Evaluation

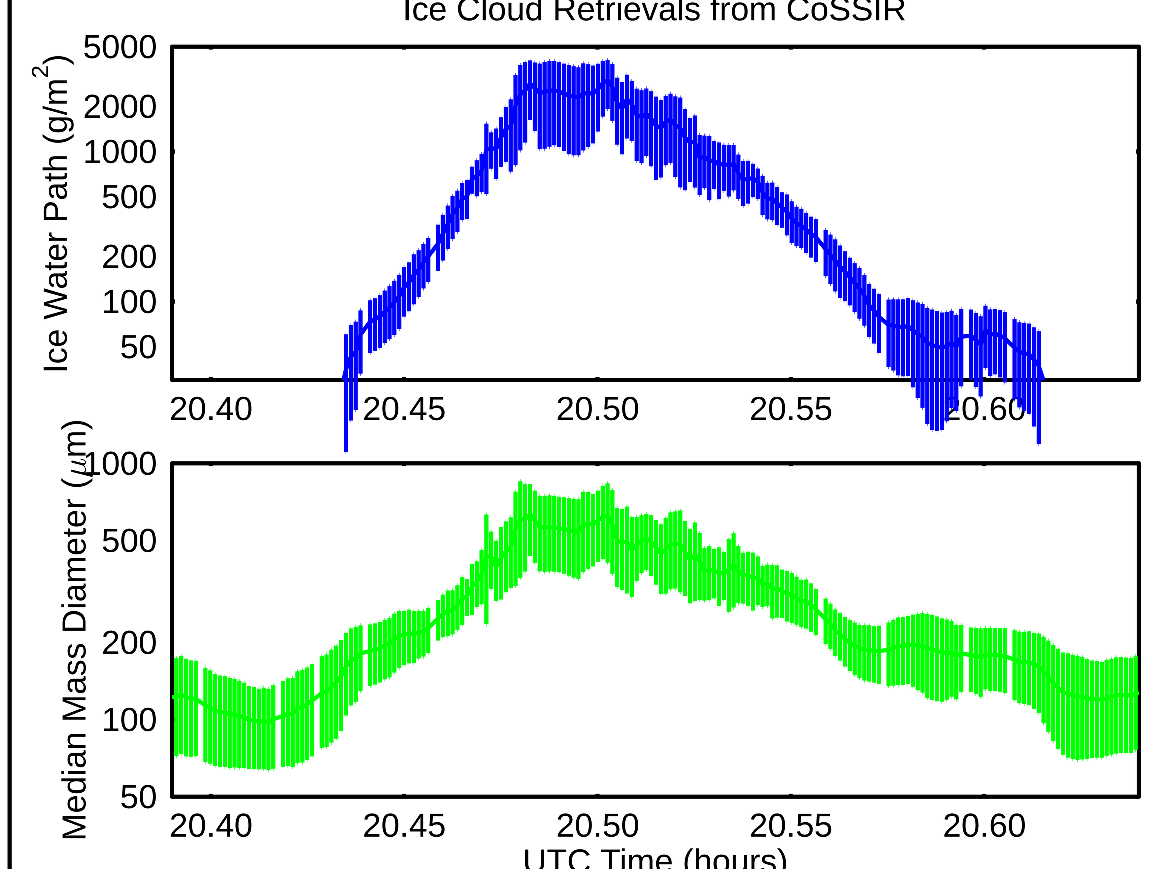
- Although CoSSIR scans cross-track we only use the nadir data for comparison with the nadir viewing radar.
- CoSSIR T_b data below are smoothed to reduce the 640 GHz noise.

CoSSIR Nadir T_b (July 29, 2002)

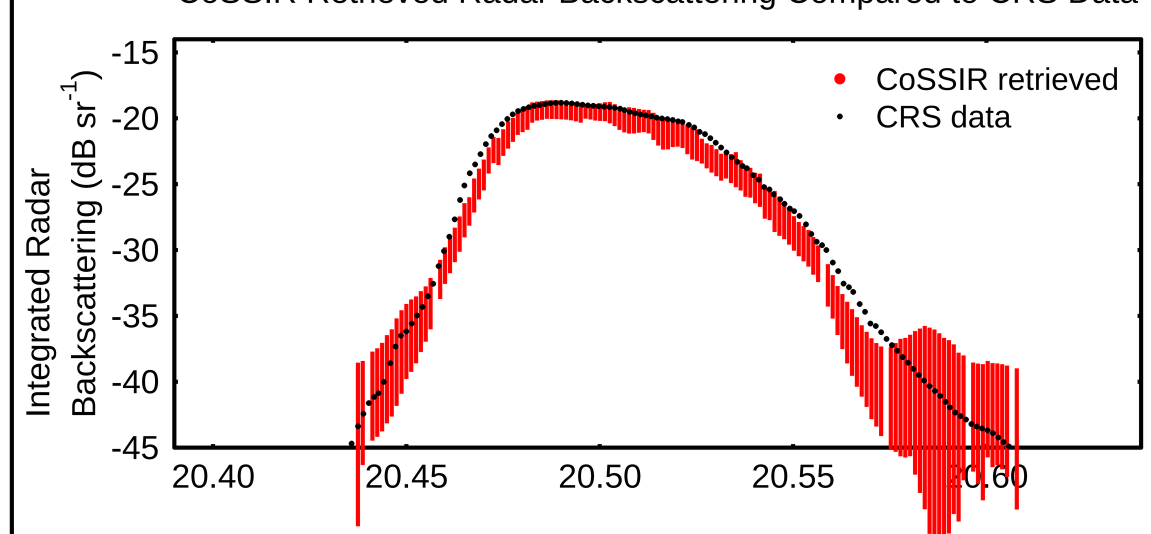


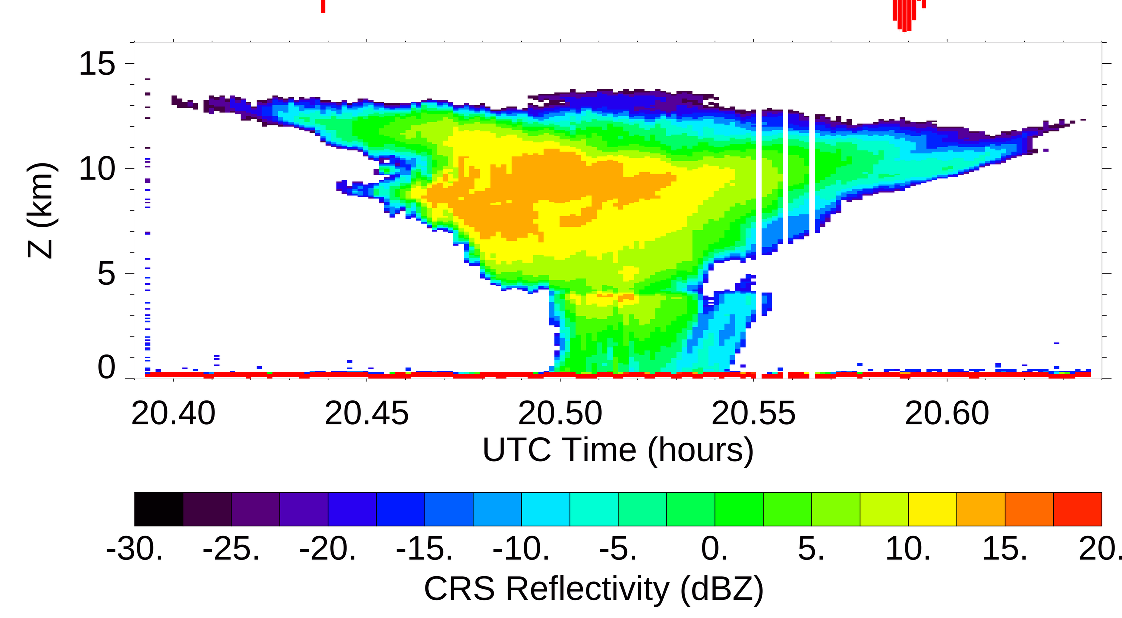
- The T_b depression at 640 GHz occurs over a wider region than at 220 GHz illustrating the greater sensitivity of the submillimeter to the smaller ice particles at the anvil edges.

Ice Cloud Retrievals from CoSSIR



CoSSIR Retrieved Radar Backscattering Compared to CRS Data





- The agreement between the CoSSIR retrieved and CRS measured integrated radar backscattering is very good, as it mostly is in seven other segments studied.

Conclusions

1) The spectral signature due to anvil ice particle scattering measured by FIRSC from 15 to 50 cm^{-1} (450 to 1500 GHz) confirms theoretical expectations.
2) Submillimeter radiometry can sense cirrus from low optical depth to thick anvils, where visible and infrared methods saturate.
3) Comparisons of FIRSC and CoSSIR retrievals with vertically integrated radar backscattering indicate that the lower microwave frequencies on CoSSIR are required for deep anvils.
4) The good agreement between CoSSIR retrievals and CRS data suggests that the CoSSIR ice cloud retrievals are valid.