Post-launch Characterisation of Satellite Instruments

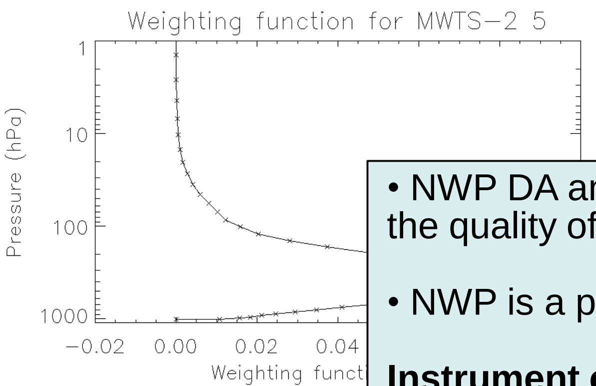
Bill Bell

Satellite Radiance Assimilation Group, Met Office

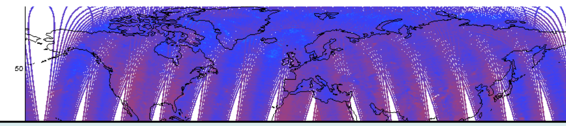
Acknowledgements

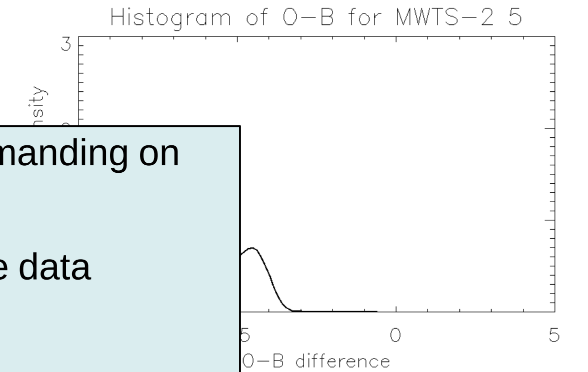
- **SSMIS**: Steve Swadley, NRL/Aerospace Cal / Val team, DMSP Program Office
- **ATMS**: Niels Bormann, Nigel Atkinson, Amy Doherty, Anne Fouilloux
- **MSU-AMSU-A**: Qifeng Lu, Katie Lean, Paul Poli, Dick Dee, Steve English
- **FY-3A / B / C**: Qifeng Lu, Katie Lean, Nigel Atkinson, Carole Peubey, Peter Bauer, Niels Bormann, Heather Lawrence, Keyi Chen.
- **TMI**: Alan Geer
- Background: Cheng-Zhi Zou, Stu Newman, Tim Hewison, Mark Jarrett, Janet Charlton

Motivation: Why invest time in characterising satellite instruments ?



Observed – Background BT for FY-3C MWTS-2 channel 5



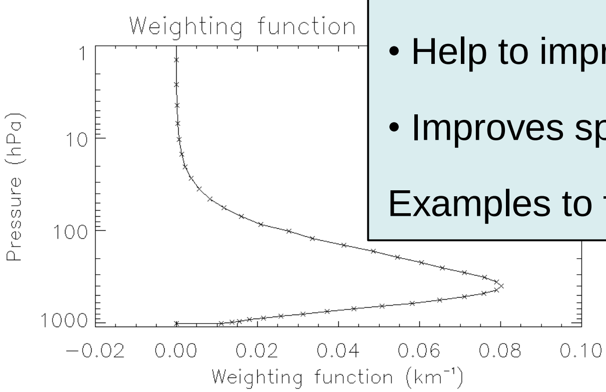


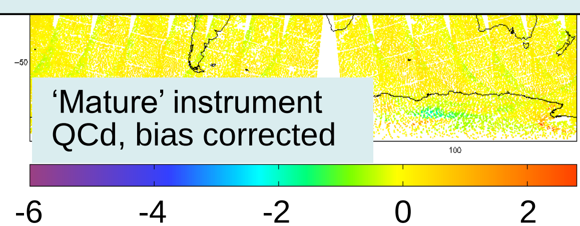
- NWP DA and climate applications are *extremely* demanding on the quality of radiance data
- NWP is a powerful tool in the assessment of satellite data

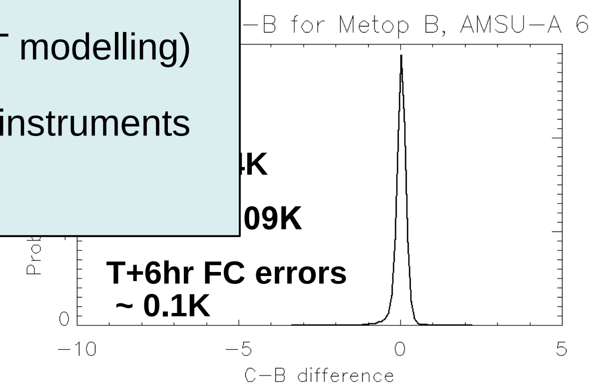
Instrument characterisation:

- Informs go / no-go decision on operational use
- Informs bias correction
- Help to improve observation operators (improved RT modelling)
- Improves specification and design of future satellite instruments

Examples to follow .....







Katie Lean

Outline

- Review approaches to post-launch characterisation (SNO, Aircraft, ground-based, ...)

- Characterisation based on NWP, examples:

  - SSMIS & TMI
  - FY-3 A & B
  - MSU & AMSU-A
  - ATMS

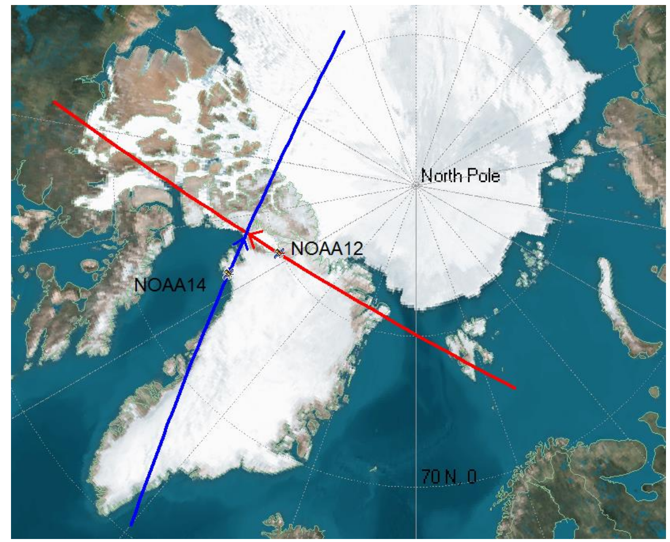
- Conclusions and Future Perspectives

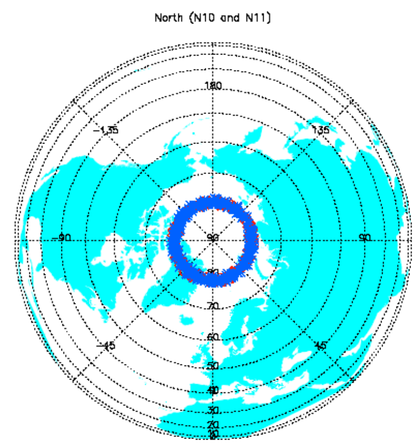
Approaches to post-launch characterisation

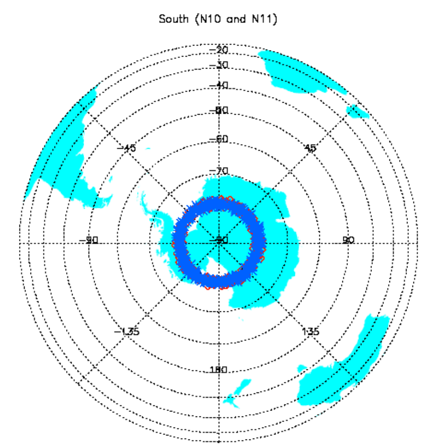
- Simultaneous nadir overpass (SNO) – *eg.* MSU & AMSU-A
- Aircraft underflights
- Ground-based observations (*eg.* GRUAN)
- Comparison with NWP
- On-orbit maneuvers
- Vicarious calibration

Simultaneous Nadir Overpass (SNO)

- Sun-synchronous satellites give SNOs in polar regions (Δx, Δt ~ 45km / 50s)
- Potential issue with dynamic range of atmospheric states (& T_B) sampled:
  - not a serious issue for temp. sounding channels
  - is a problem for water vapor channels
- **[1]** Establishes **inter-satellite biases**
- **[2]** Estimated biases modeled by a range of parameters / mechanisms, including:
  - Bias shifts and drifts
  - Instrument temperature related variability
  - Scene temperature dependent biases
  - Channel frequency shifts



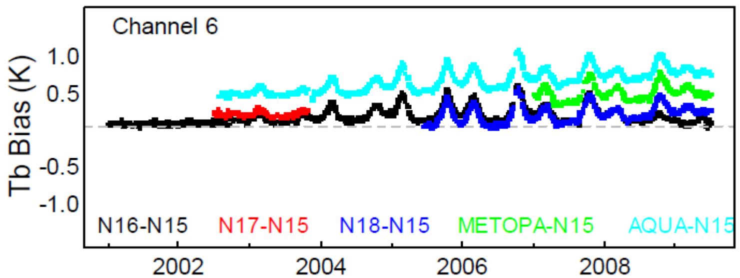




Cheng-Zhi Zou, NOAA

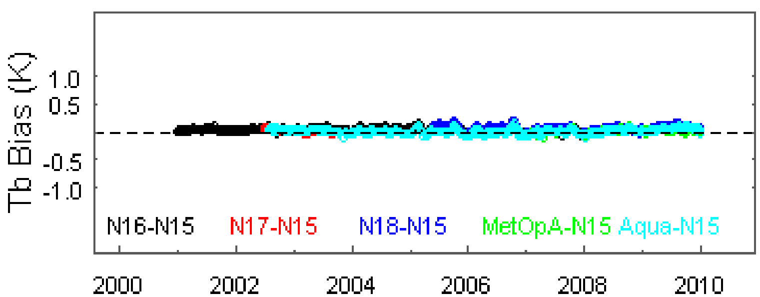
Simultaneous Nadir Overpass
AMSU-A recalibration
Zou and Wang, JGR, 2011.

SNO diagnosed biases

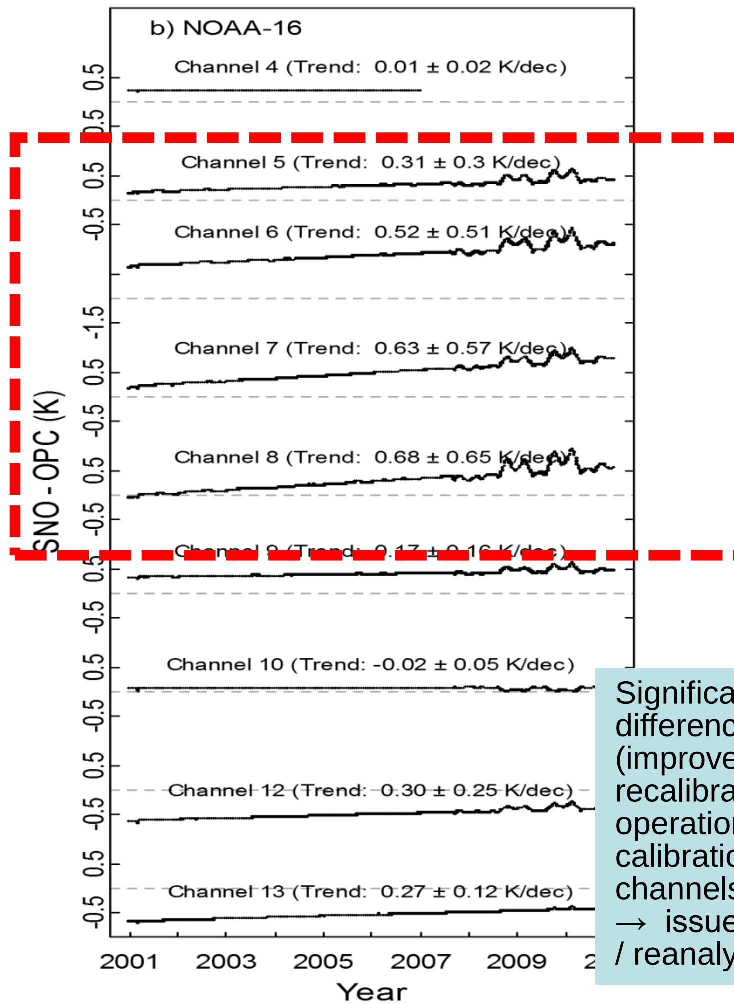


Biases modelled and corrected, using:

- a radiance offset
- a radiance slope
- radiometer non-linearity
- a frequency shift (NOAA-15 only)

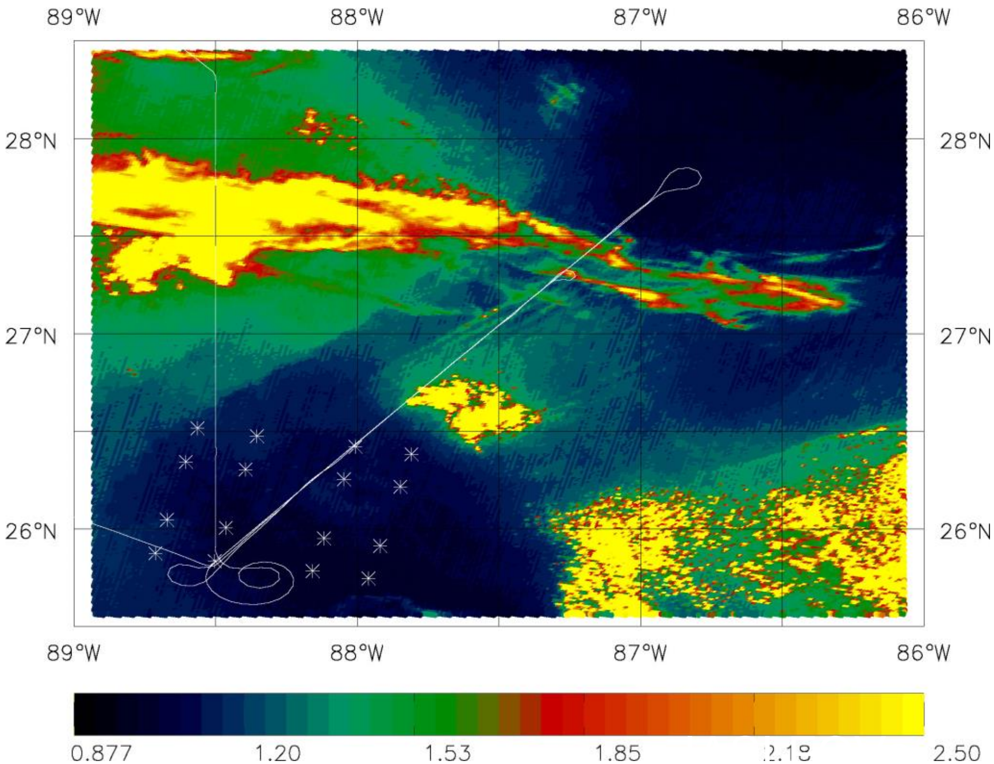


SNO recalibrated - operational calibration



Significant differences in (improved) SNO recalibrated vs operational calibration for channels 5-8 → issue for climate / reanalysis

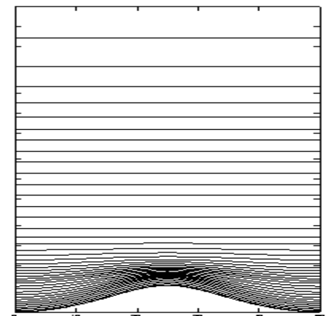
Aircraft underflights
e.g. JAIVEx Metop-A IASI *vs* ARIES
Gulf of Mexico 30/4/2007



AVHRR channel 1 image from MetOp on 30 April 2007

JAIVEx campaign, Stu Newman (A. Larar, ACP, 2010)

top of atmosphere (MetOp)



Model fields from Met Office UM and ECMWF analyses

BAe 146 max alt.

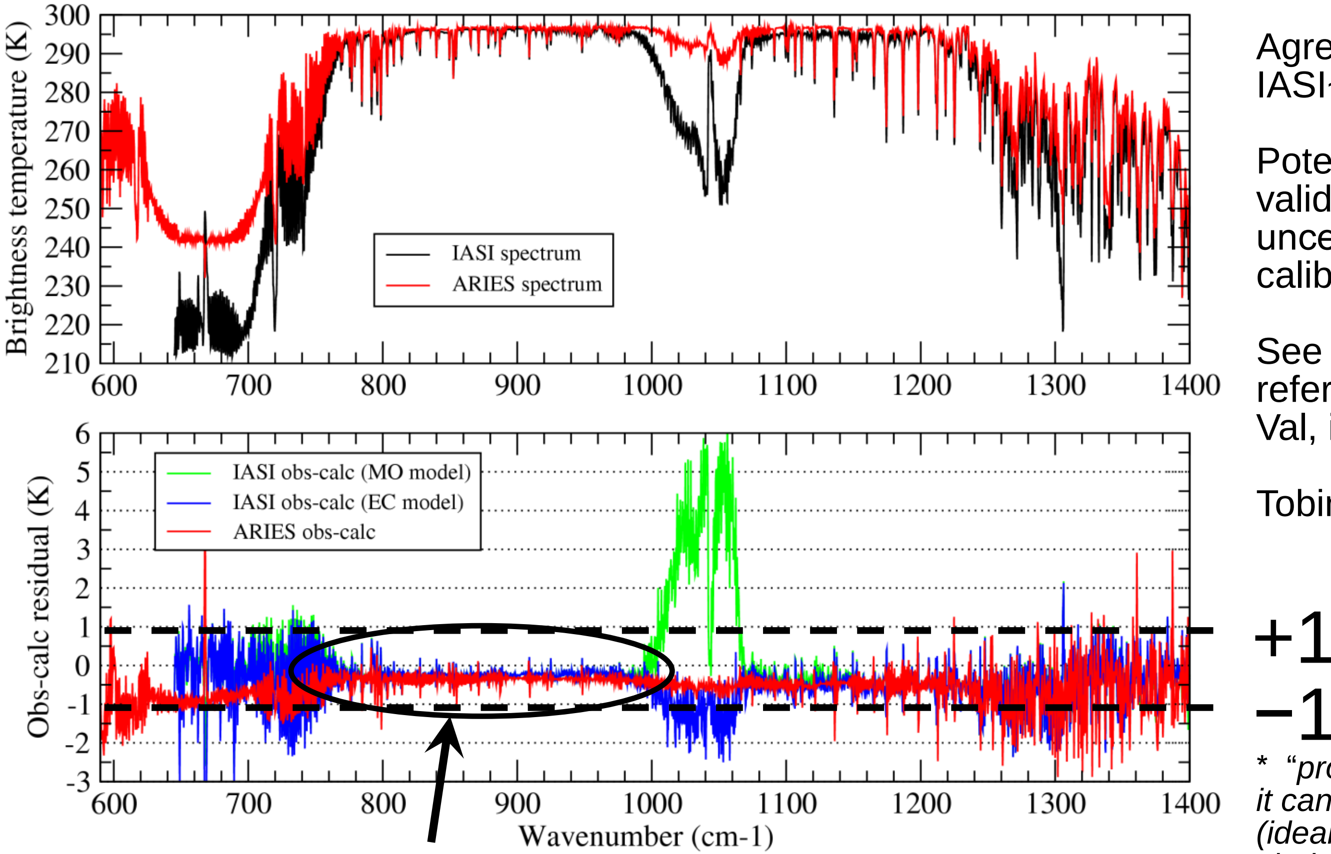
Dropsondes and FAAM 146 in situ measurements

T_{skin} (100 feet)

surface

Aircraft underflights

Met Office



Window region residual ≈ −0.2 K

Agreement between ARIES and IASI~ 0.1K

Potentially offers definitive validation of satellite radiometric uncertainties using traceably* calibrated airborne radiometers

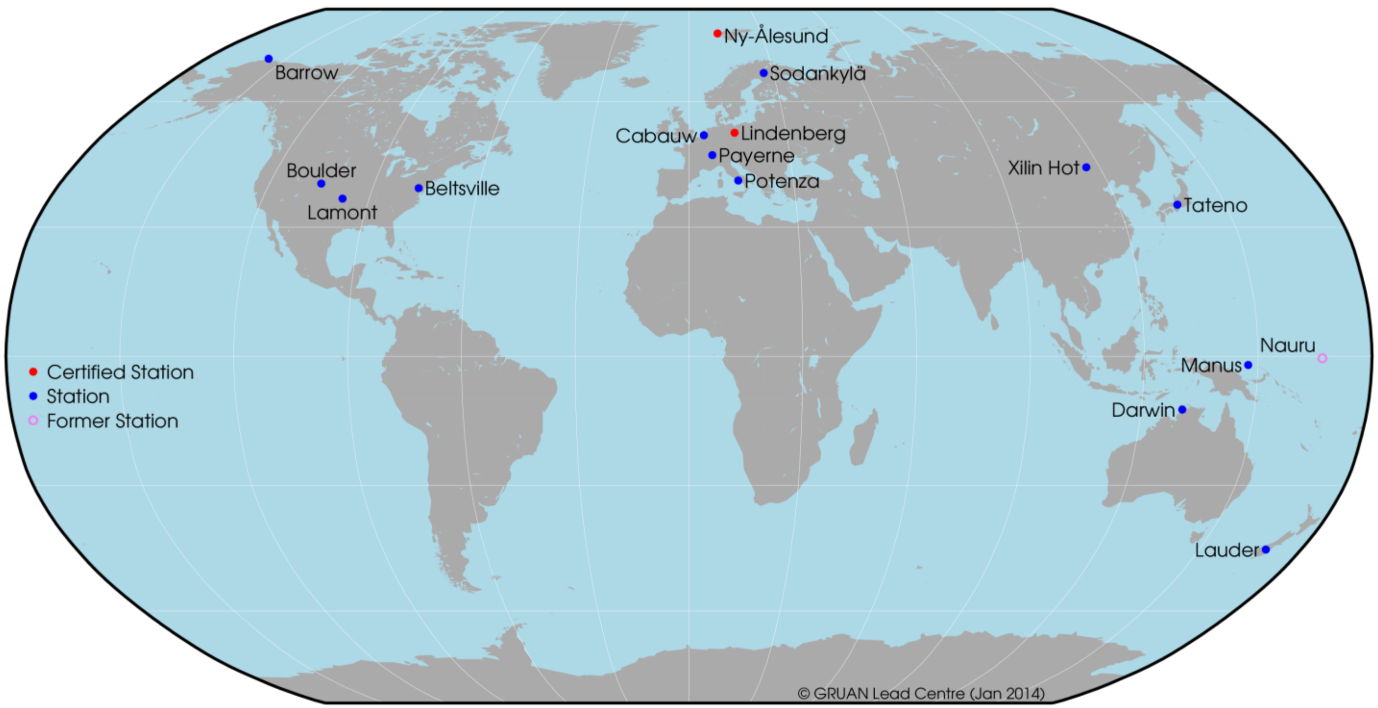
See Smith *et al* (ITSC-19) for references to S-NPP CrIS Cal / Val, including:

Tobin *et al*, JGR, 2013.

* *"property of a measurement whereby it can be linked to primary standards (ideally the SI) through an unbroken chain of comparisons"*

Ground-based *e.g.* GRUAN

GCOS Reference Upper-Air Network



- GRUAN aims to provide high quality, traceable, measurements for climate studies & the validation of satellite observations (*e.g.* Calbet, ITSC-19)

- How ? – EU's GAIA-CLIM project (see later)

Post-launch characterisation using NWP

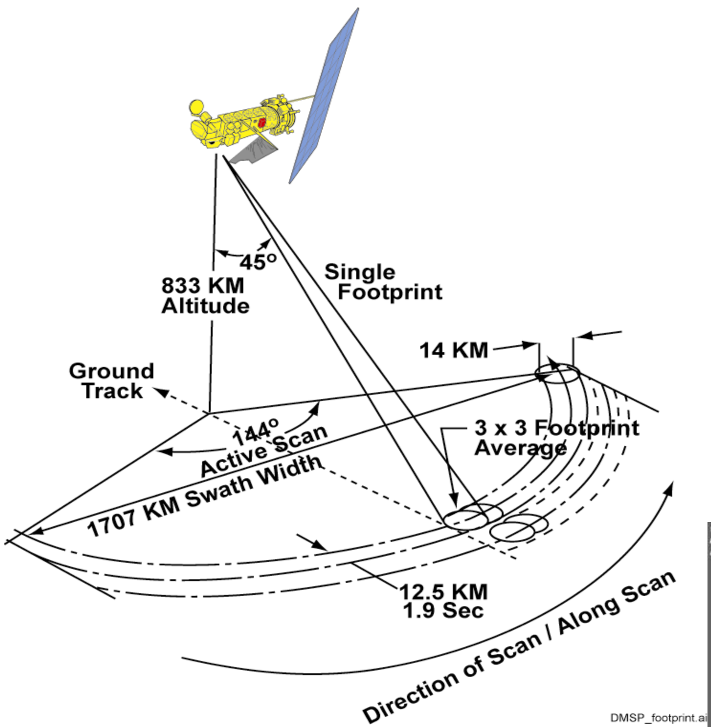
- **SSMIS** - reflector emission, warm load intrusions
- **TMI** – reflector emission
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A -** pass band shifts and drifts
- **ATMS** - striping (1/f calibration noise)

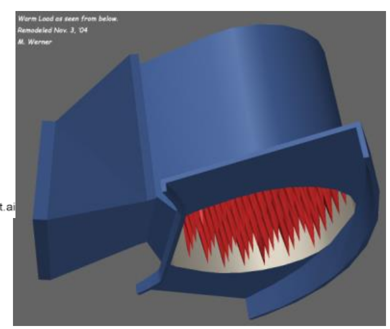
Post-launch characterisation using NWP

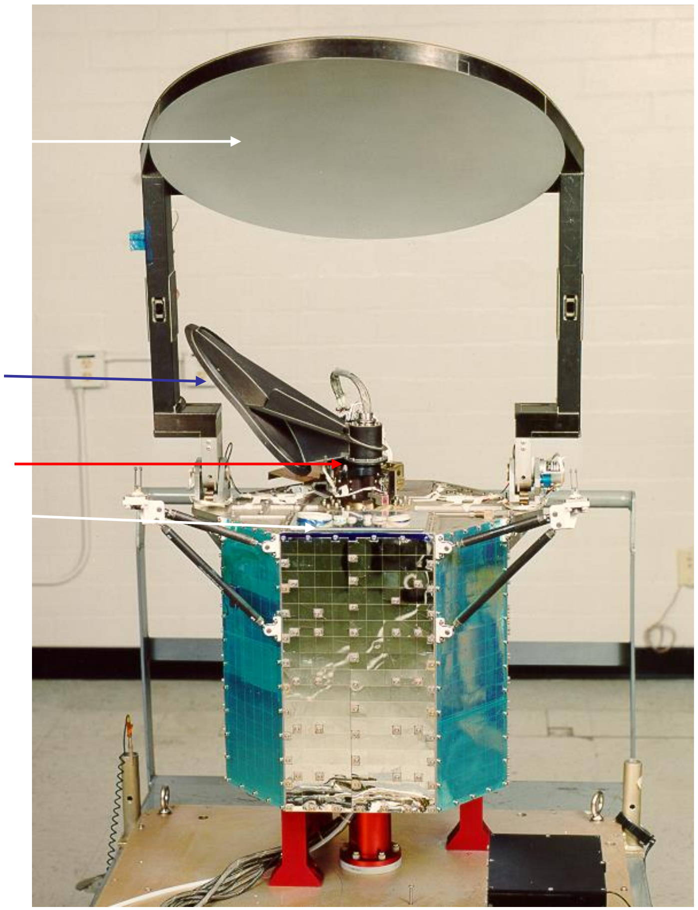
- **SSMIS** - reflector emission, warm load intrusions
- **TMI** – reflector emission
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A**: pass band shifts and drifts
- **ATMS**: striping (1/f calibration noise)

SSMIS: Instrument and scan geometry

Special Sensor Microwave Imager / Sounder (SSMIS)

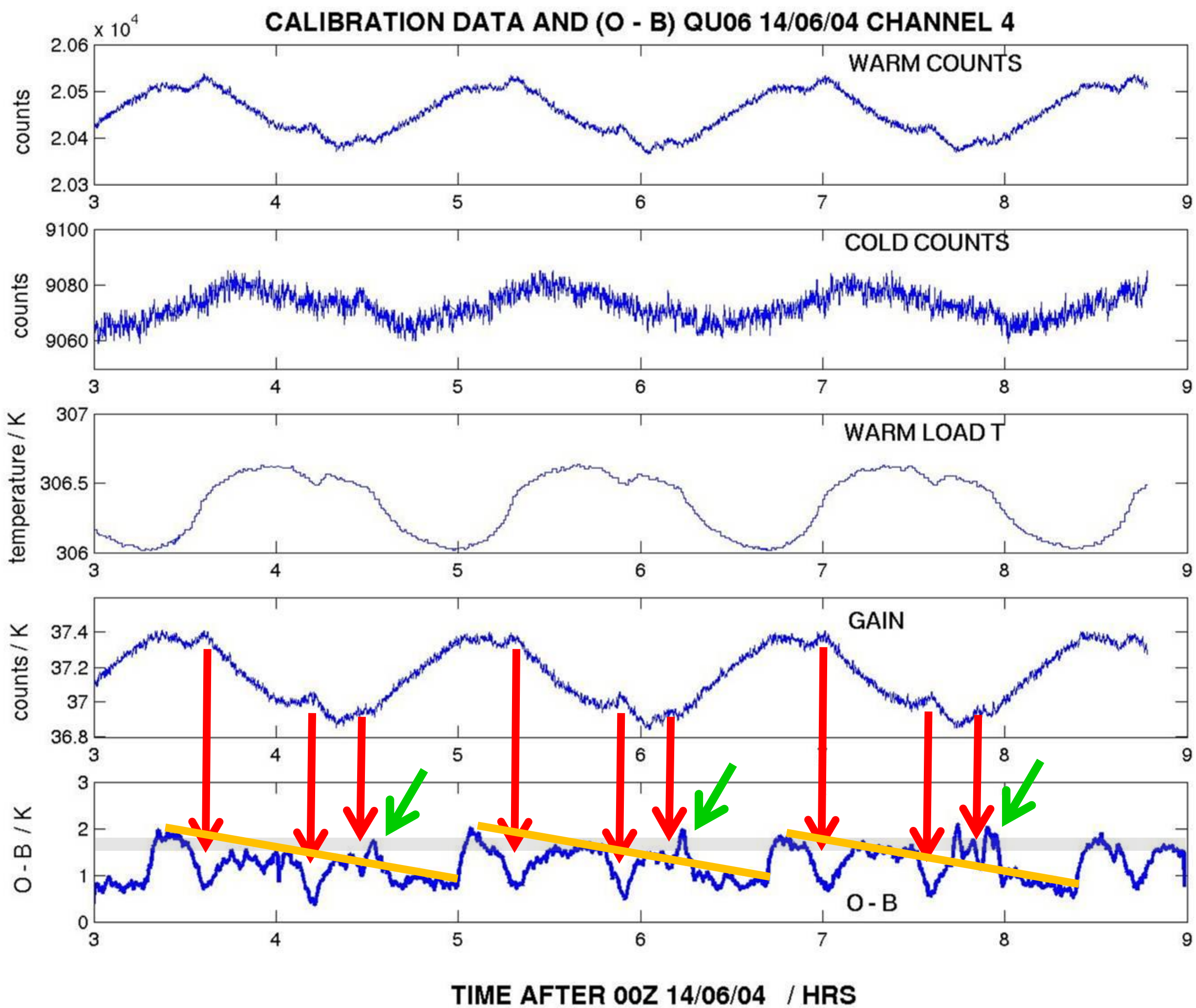


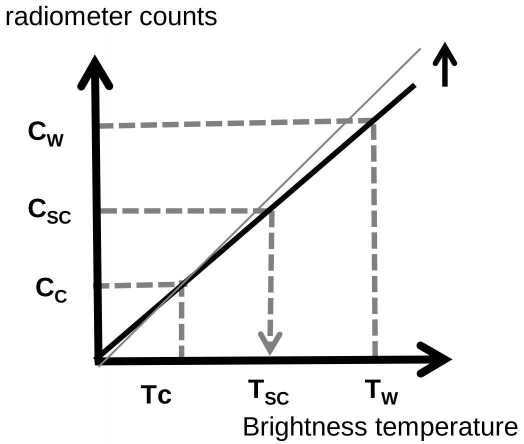




- Combined imaging (19 GHz – 91 GHz, 150 GHz) & sounding (50 - 60 GHz, 183 GHz) capabilities
- First launched 2003 (F-16). Currently 4 SSMIS instruments on orbit (F-16 – F-19)
- Open design made calibration challenging

SSMIS Instrument biases:
warm load solar intrusions & reflector emission





Grey bar shows expected (1σ ~ 0.15K) envelope for averaged O-B

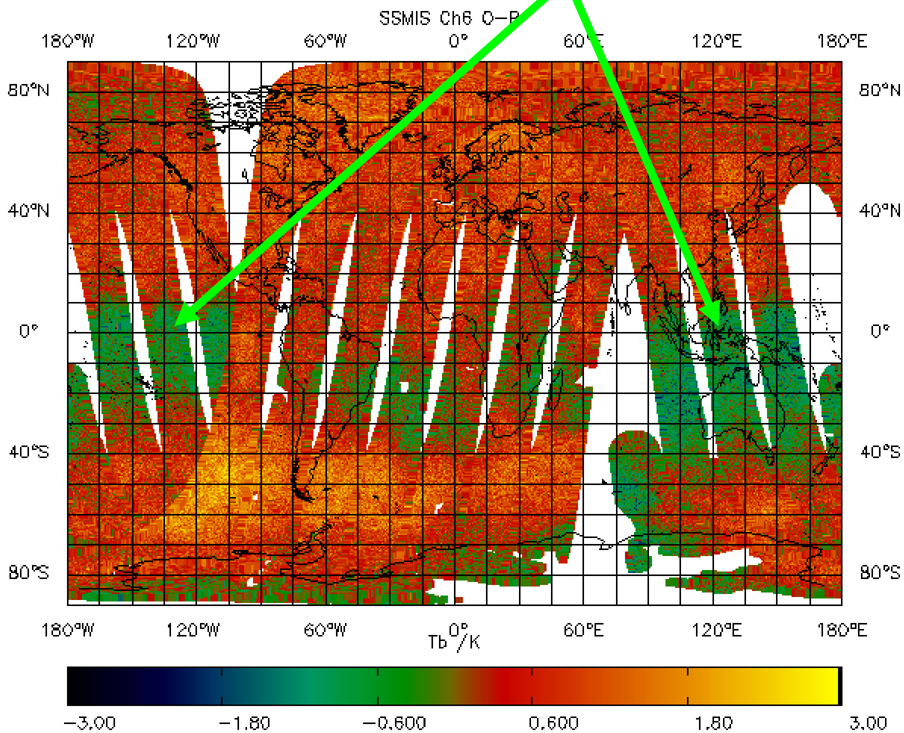
Gain anomalies (caused by solar intrusions into warm load)

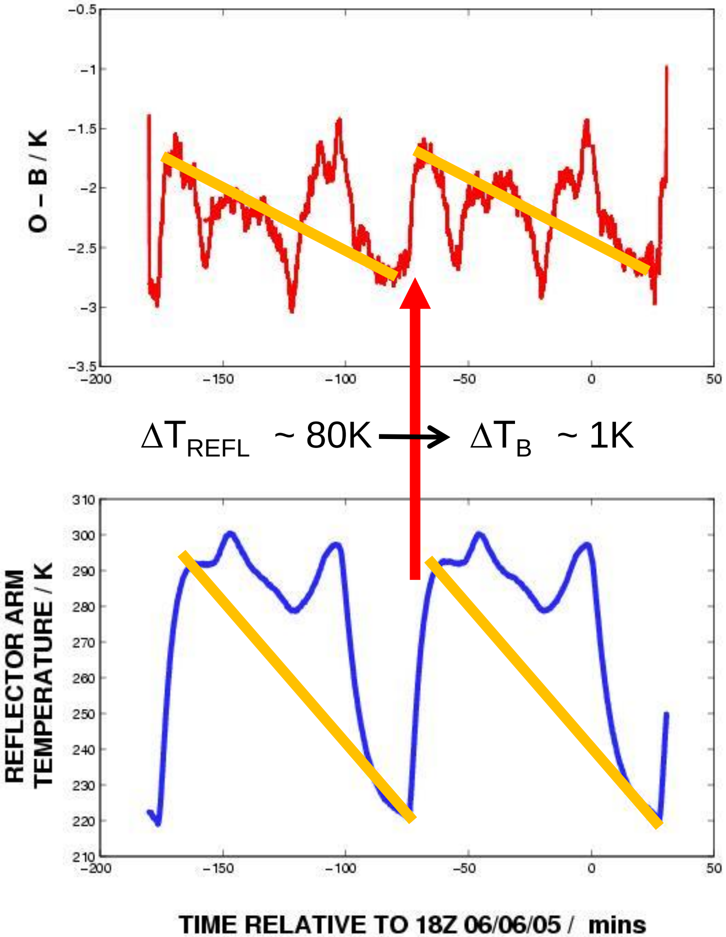
Reflector emission anomaly

Also reflector emission anomaly- but highlighted the need for improved antenna temp measurements

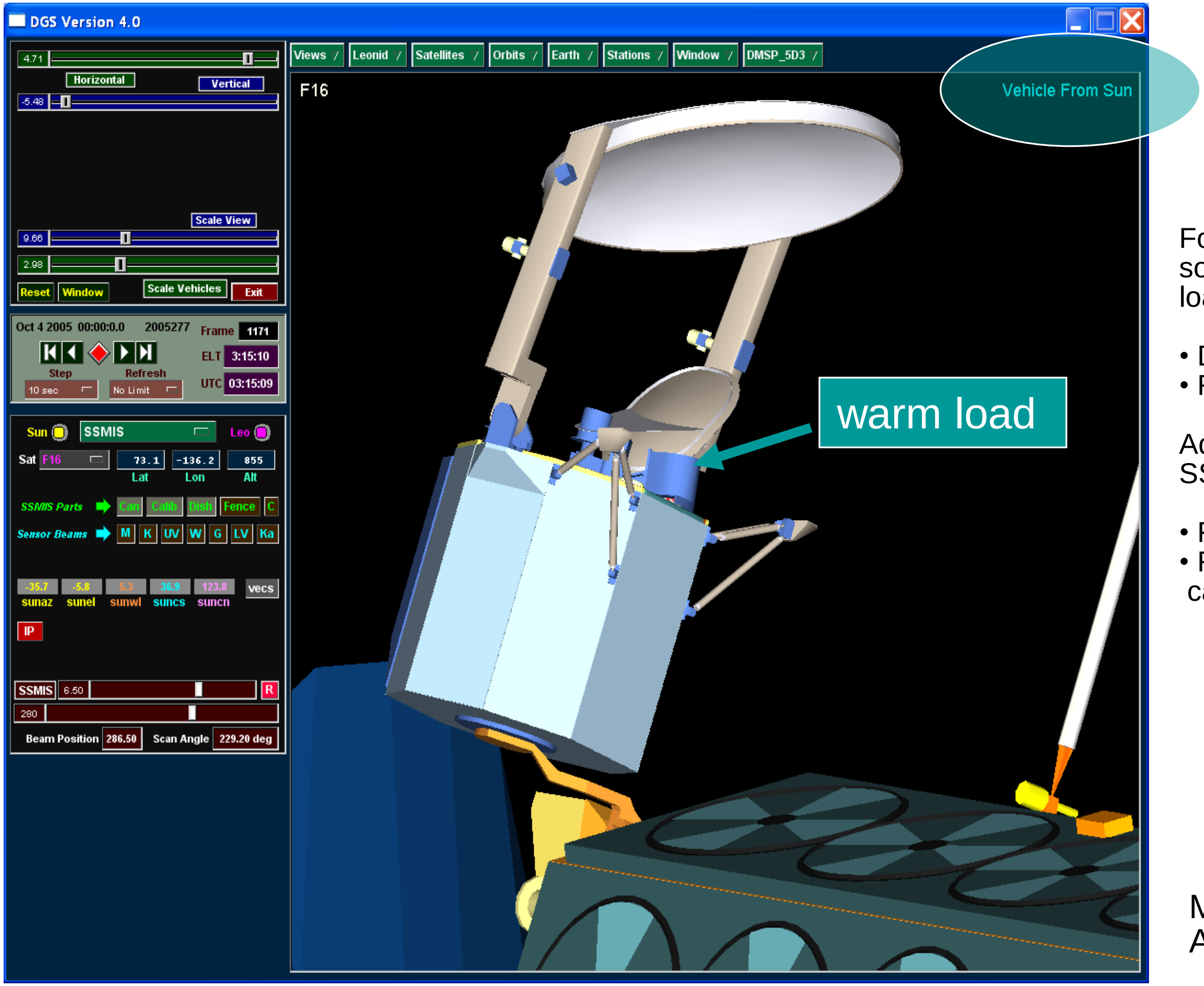
SSMIS Reflector emission

Problems in ascending node not evident in descending node





SSMIS instrument biases: warm load solar intrusions



For F-16 - 3 or 4 times per orbit solar radiation illuminates warm load tines, through:

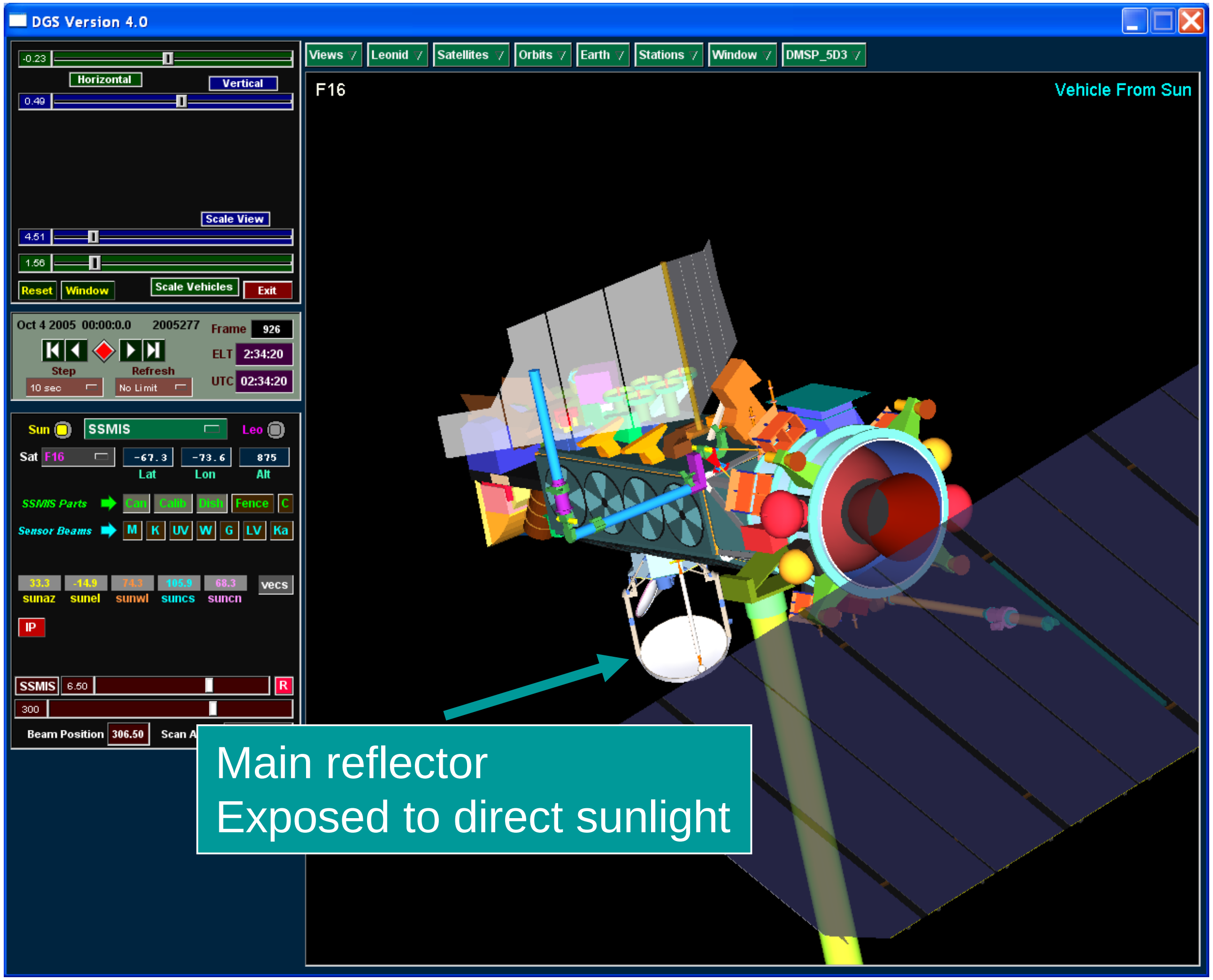
- Direct illumination ; or
- Reflected illumination

Addressed in subsequent SSMIS instruments through:

- Fence; and
- Reducing reflectivity of the canister top

Mike Werner
Aerospace Corp.

SSMIS instrument biases:
Reflector emission - entering Earth shadow



Mike Werner
Aerospace Corp.

SSMIS instrument biases
Reflector emission - leaving Earth shadow

DGS visualisation software was an essential complement to NWP-based diagnostics:

- In understanding root causes
- Improving the design of subsequent instruments.

Mike Werner
Aerospace Corp.

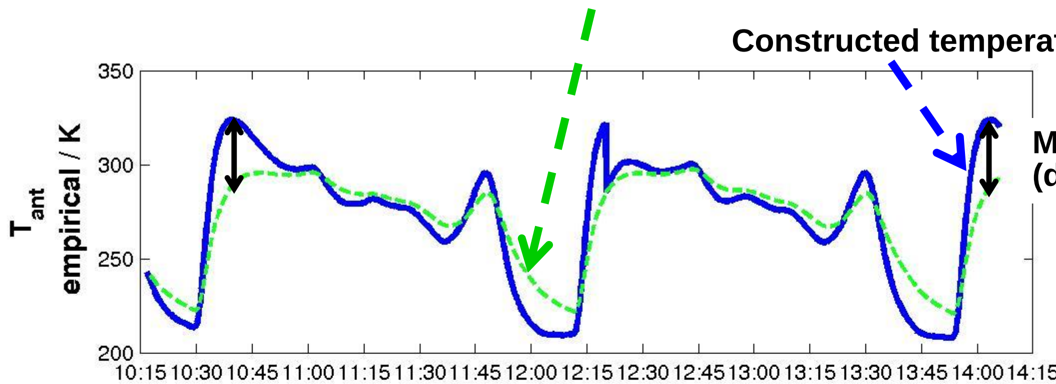
Modelling SSMIS reflector emission

Met Office

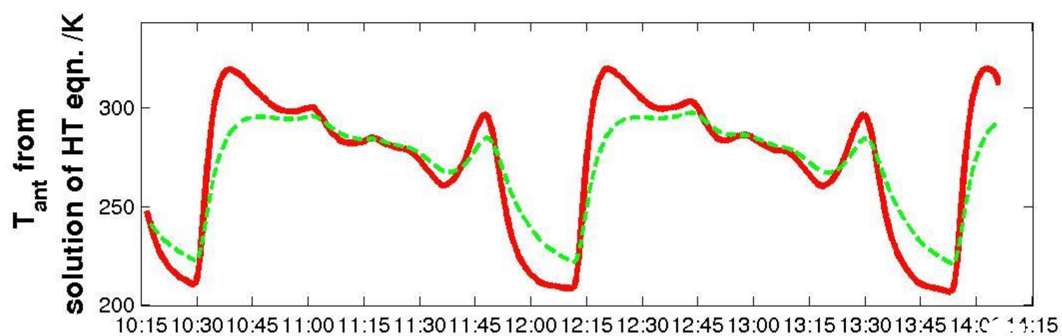
Correction for reflector emission required: reflector temperature (t) & ε (v)

Measured temperature of reflector support arm

Constructed temperature of reflector surface



Max. amplitude of correction ~40K (derived from NWP / RT modelling see next)

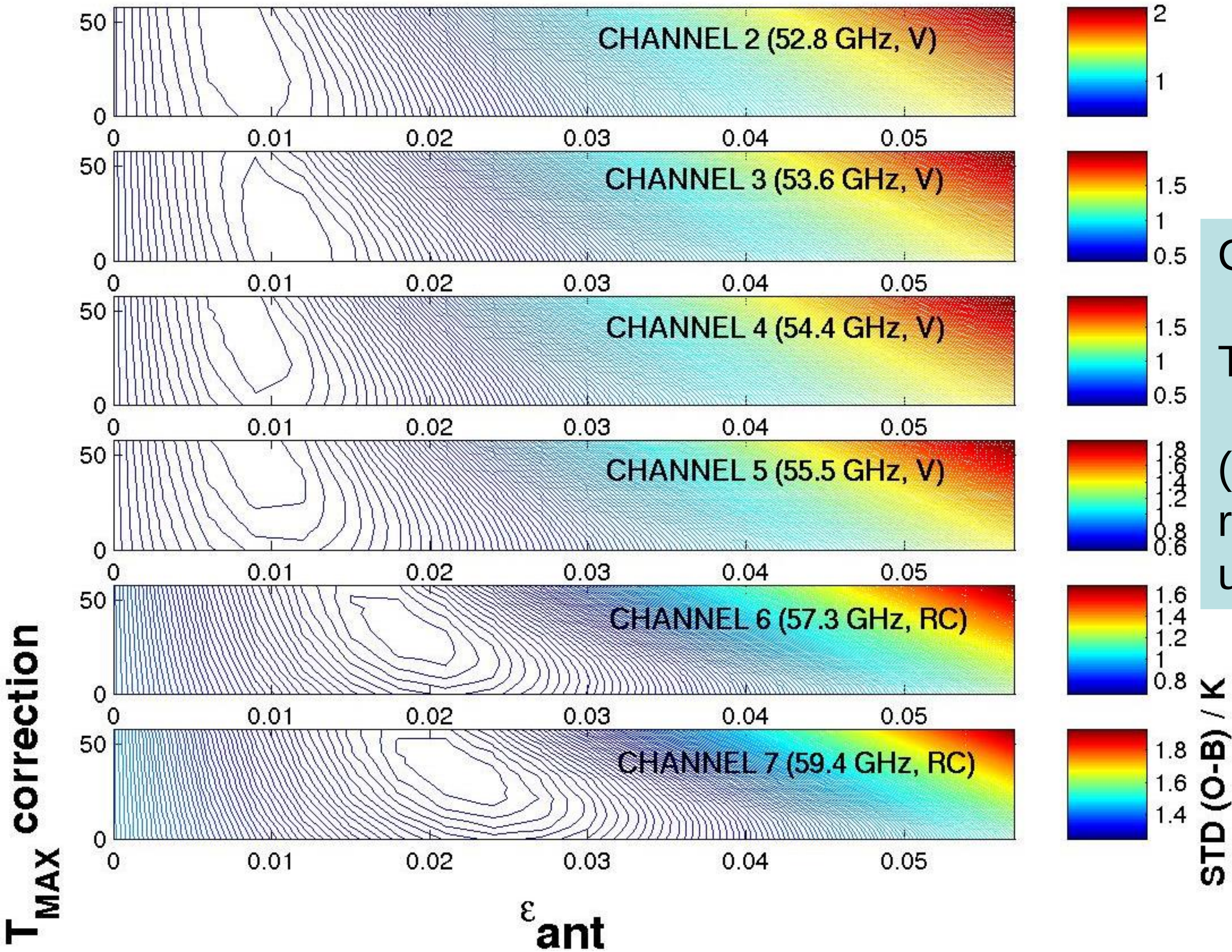


Reasonable agreement with temperature evolution derived from solving the heat transfer equation

Bell et al, TGARS, 2008

Characterising T_{ANT} & ε : Chs 2 – 7

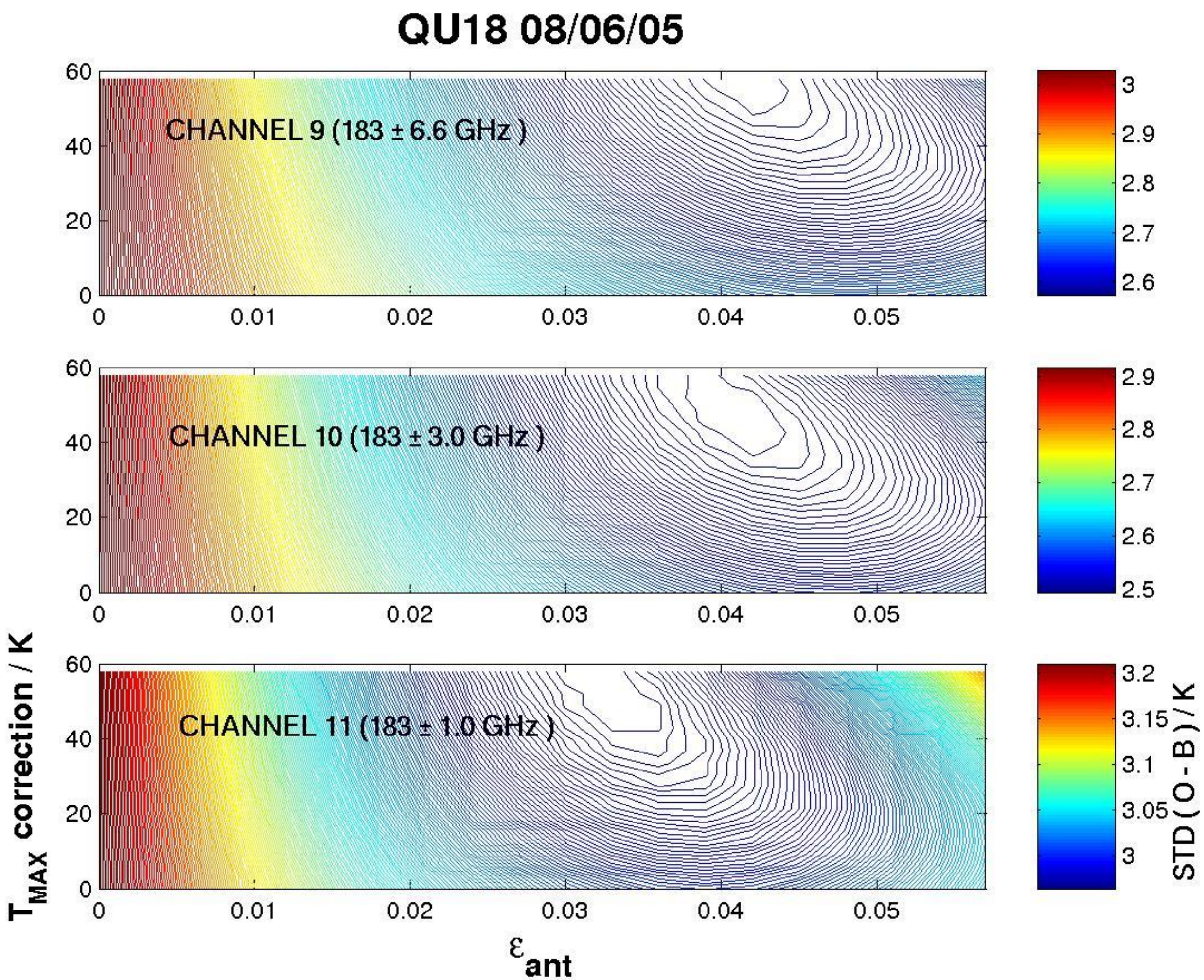
Temp sounding channels



Ch 1 - 5 : ε = 0.01
6,7 : ε = 0.02
T corr = 30 – 40 K

(effectively calibrating reflector emissivity using NWP T fields!?)

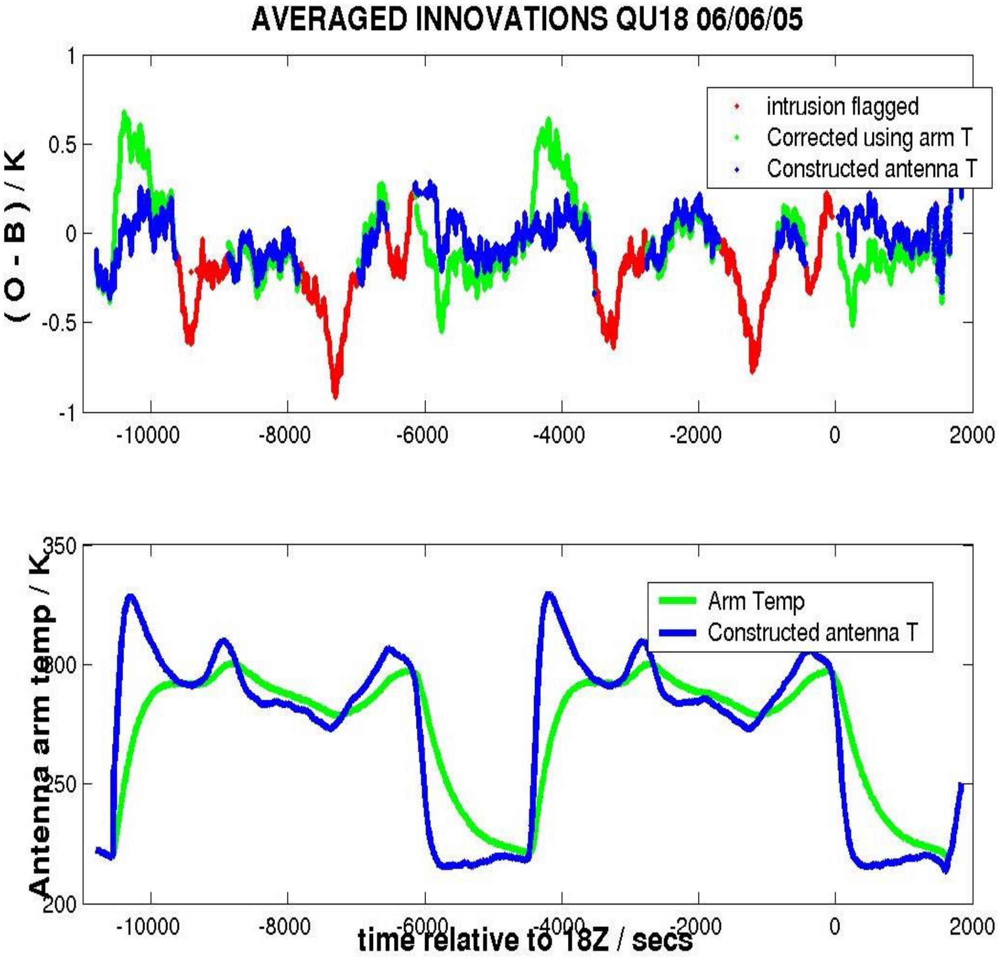
Characterising T_{ANT} & ε : Chs 9 - 11



Q sounding channels (MHS like)

Determination of ε less precise due to larger uncertainties in NWP q fields

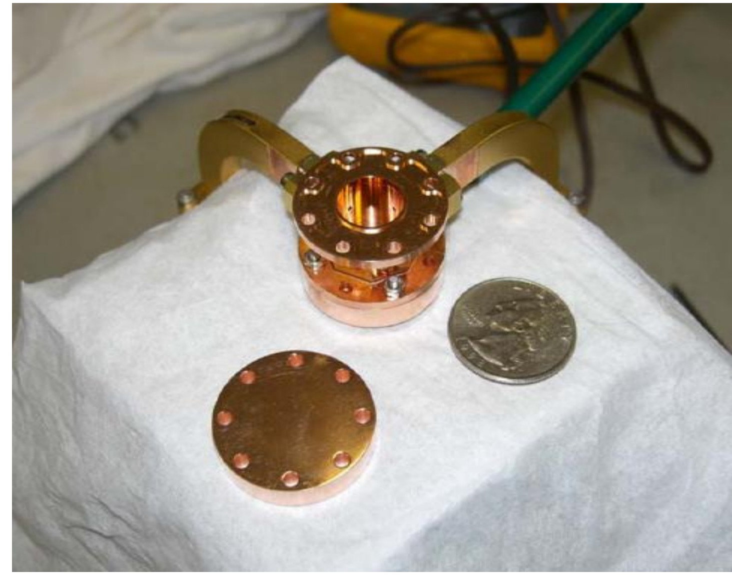
SSMIS – antenna emission correction using constructed antenna T



Met Office

Measurements of reflector emissivity

Aluzio Prata & Shannon Brown
USC / JPL



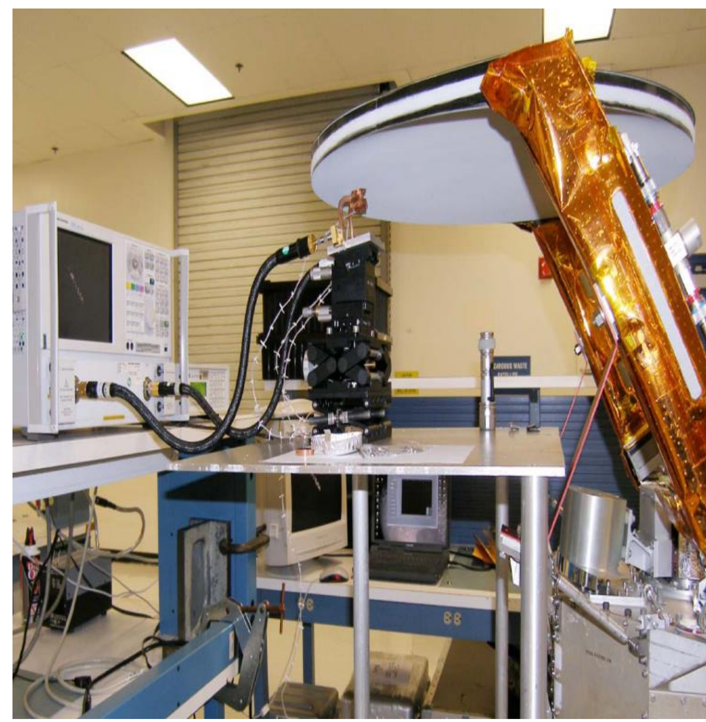
$$\varepsilon_v \cong \sqrt{\frac{16\pi\upsilon\varepsilon_0}{\sigma}}\sec\theta_i$$

Effective Conductivity, σ [MS/m]

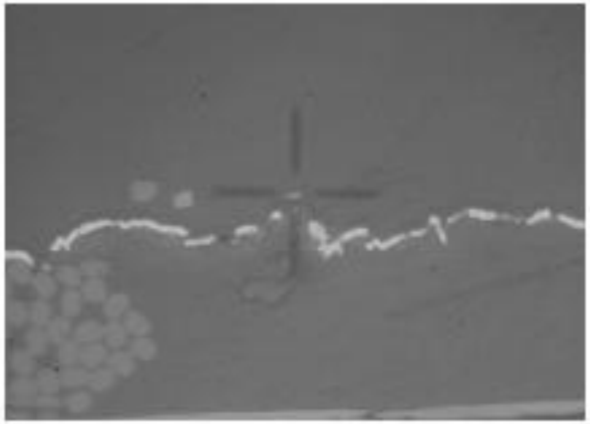
183 GHz Pure Al at 300 K
$\Theta_i = 18^\circ$
$\sigma = 36.59$ MS/m

$$\varepsilon_v = 0.00157$$

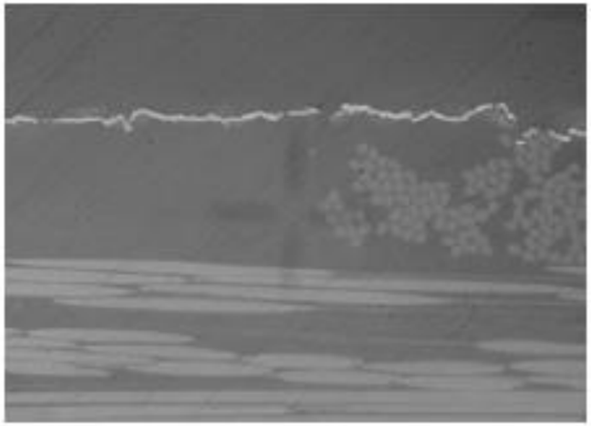
$$\varepsilon_h = 0.00142$$



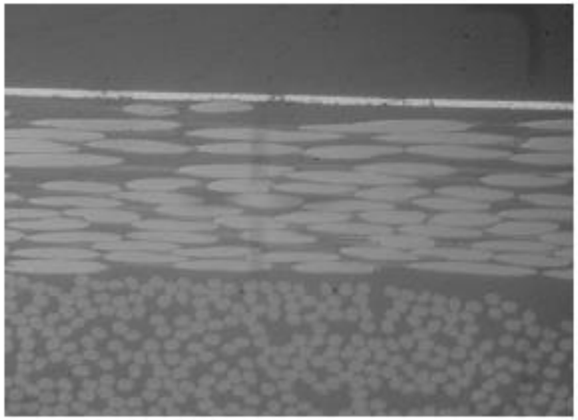
Measurements of reflector emissivity
The role of surface roughening



32 GHz σ_E = 3.4 MS/m
55 GHz ε = 0.0027

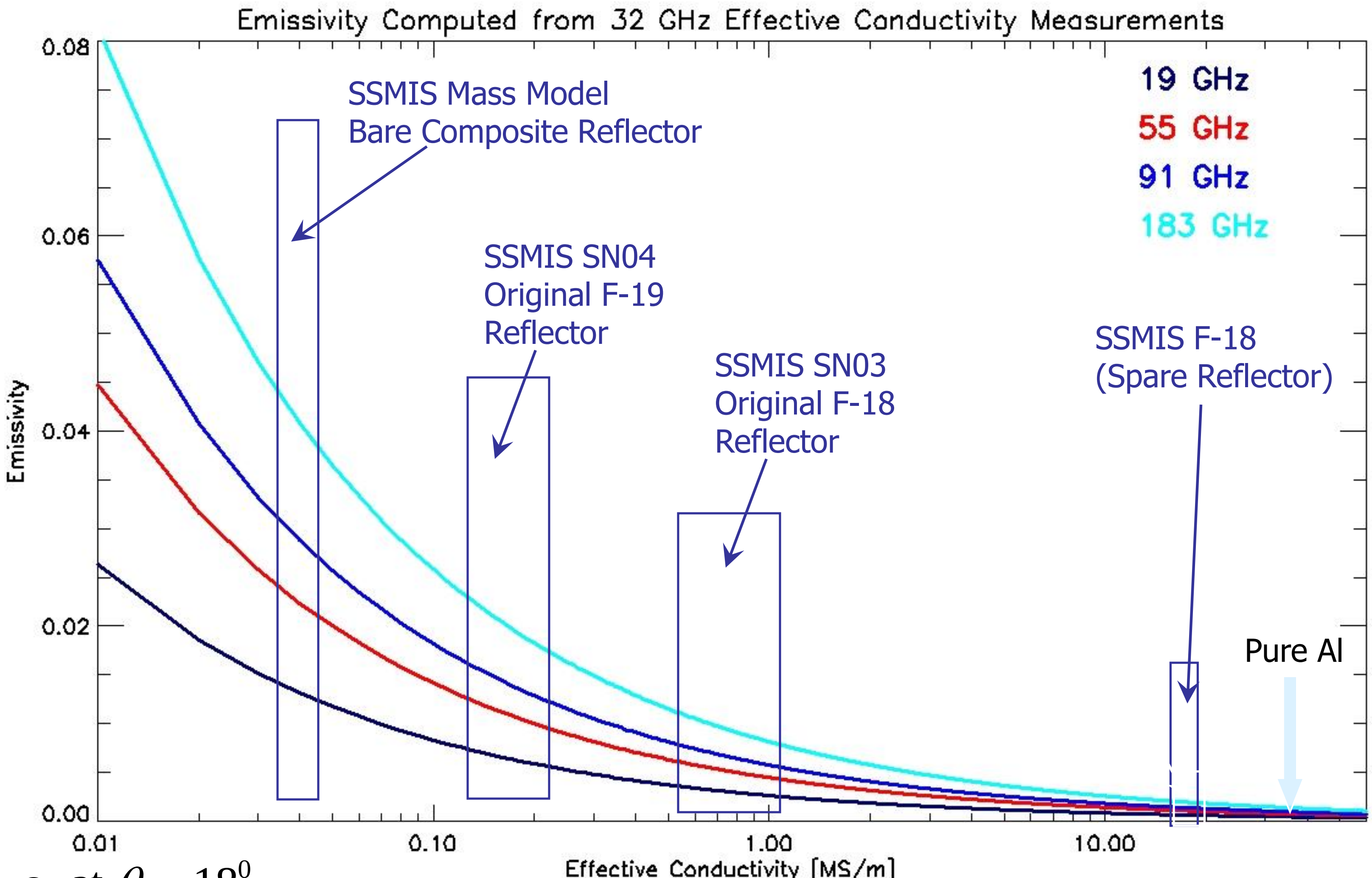


32 GHz σ_E = 9.1 MS/m
55 GHz ε = 0.0016



32 GHz σ_E = 33 MS/m
55 GHz ε = 0.0009

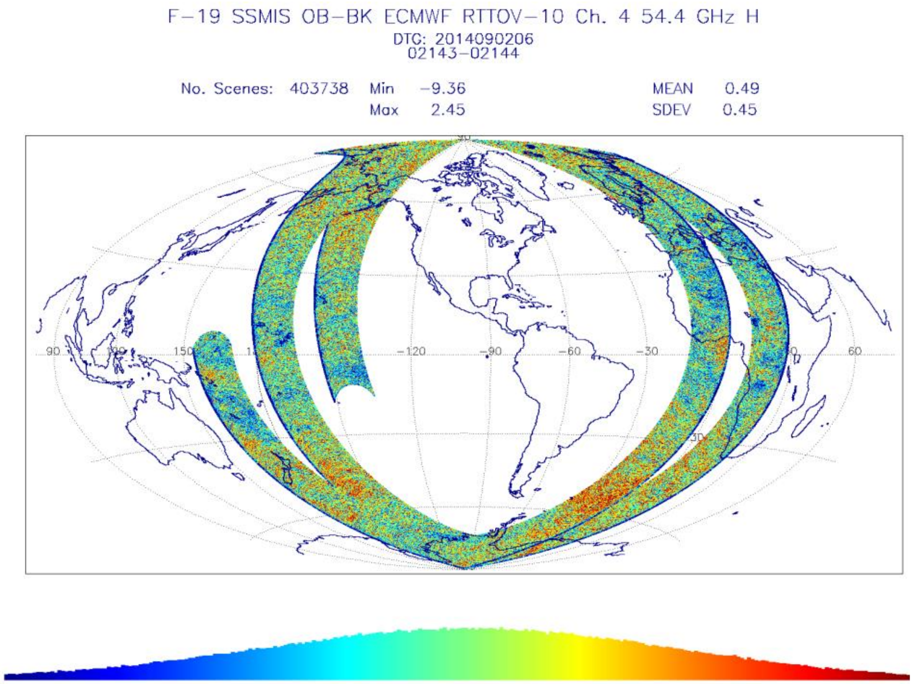
Measurements of reflector emissivity
The role of surface roughening

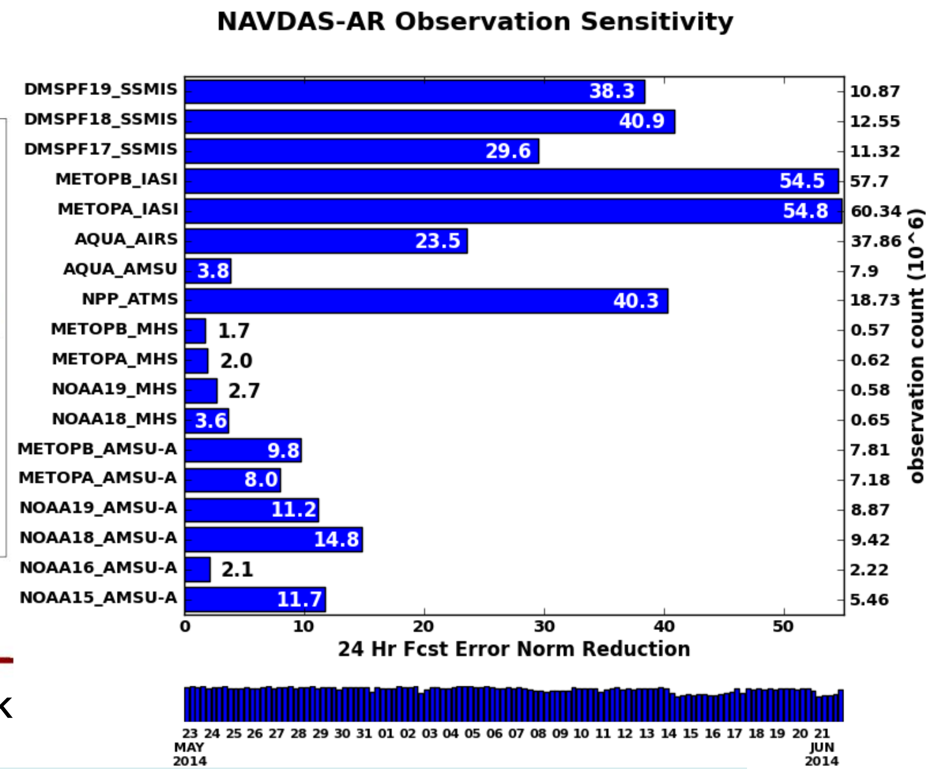


ε_h at $\theta_i = 18^0$

SSMIS status and plans F-19

Steve Swadley, NRL



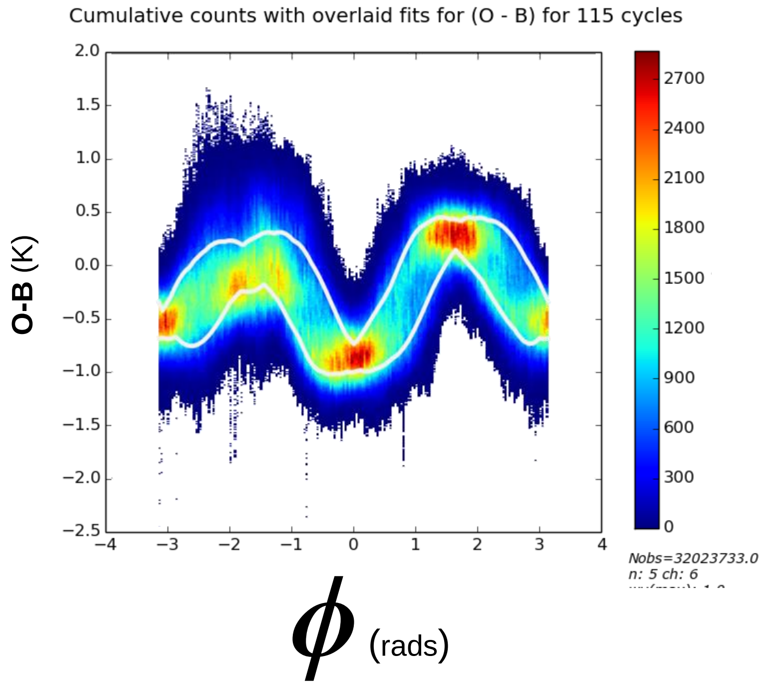


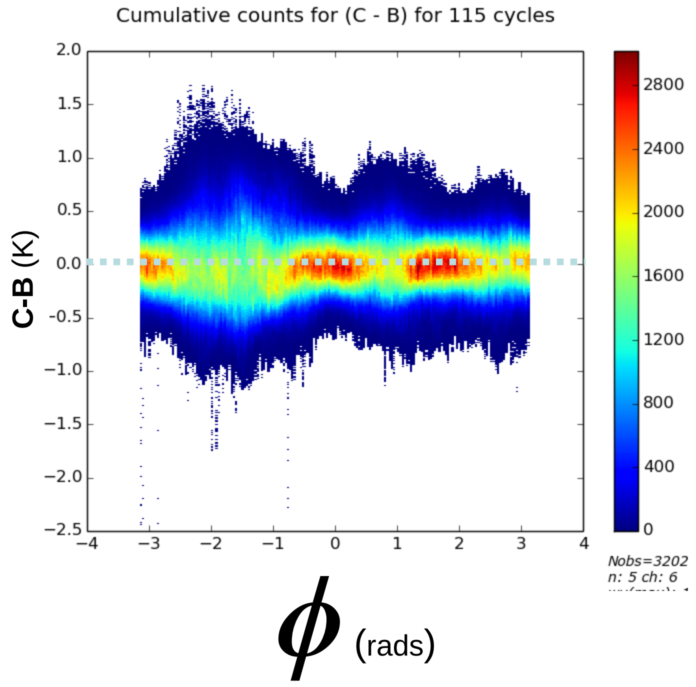
- F-19 SSMIS (launched April 2014) under evaluation at NRL
- Initial indications are that temperature sounding channels are free of reflector emission biases.
- Early assimilation experiments show F-19 performing well in NAVDAS-AR.

Plots reproduced with the permission of DMSP Program Office and NRL / Aerospace Cal/Val team.

SSMIS status and plans
- a new bias predictor model to deal with orbital biases

Evolving (VarBC) Fourier series expansion in orbital angle (φ) shows promise in correcting complex orbital biases.



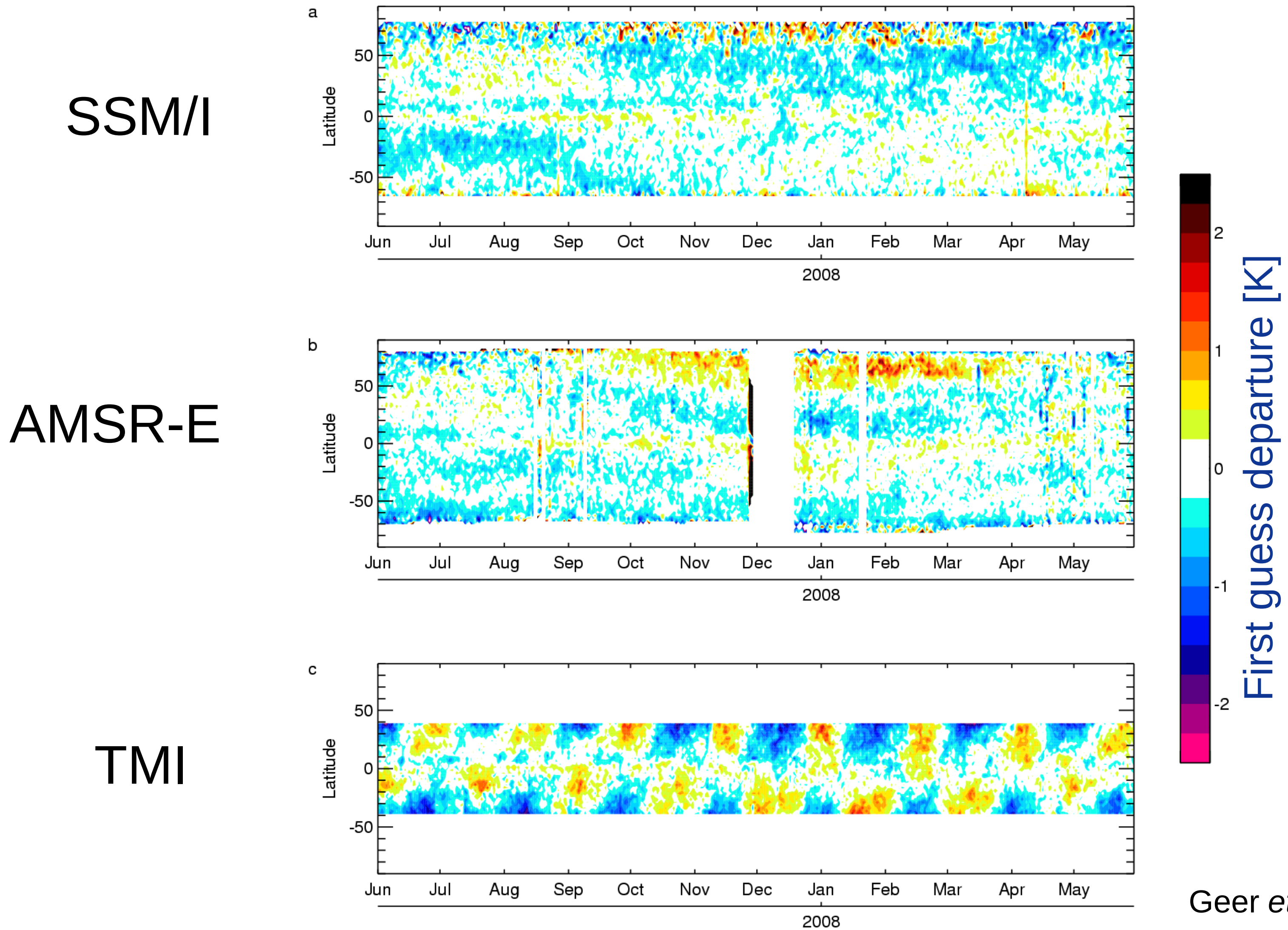


Anna Booton

Post-launch characterisation using NWP

- **SSMIS** - reflector emission, warm load intrusions
- **TMI – reflector emission**
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A**: pass band shifts and drifts
- **ATMS**: striping (1/f calibration noise)

Reflector emission in TMI

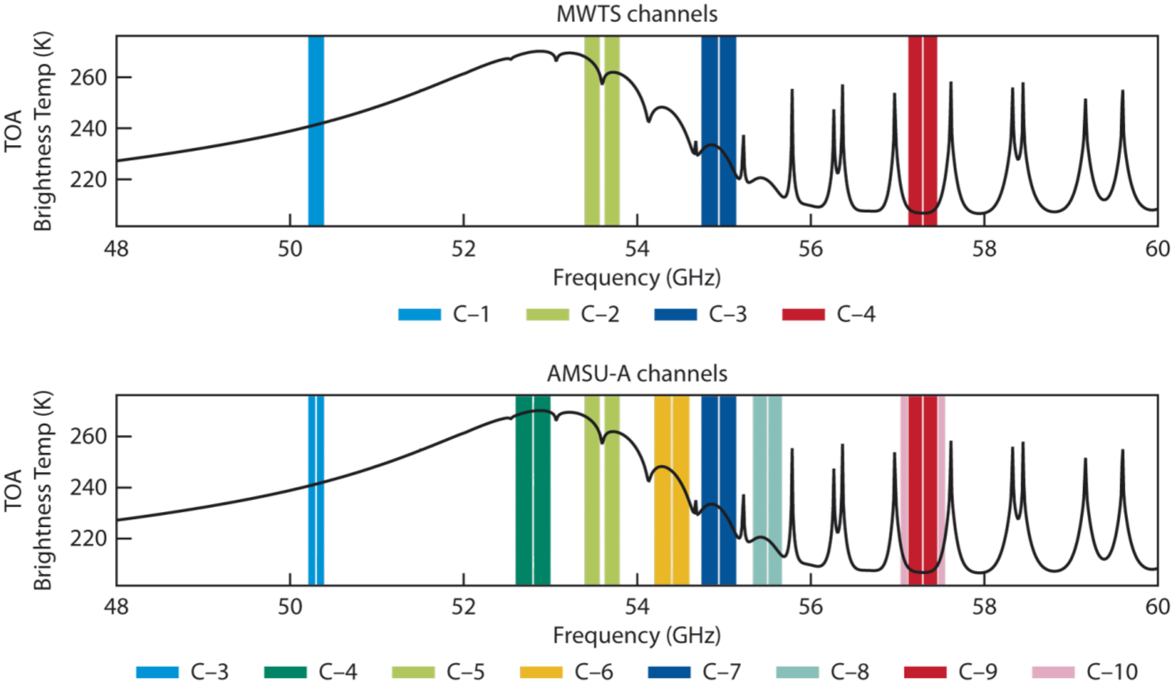


Geer *et al*, TGARS, 2010

Post-launch characterisation using NWP

- **SSMIS** - reflector emission, warm load intrusions
- **TMI – reflector emission**
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A**: pass band shifts and drifts
- **ATMS**: striping (1/f calibration noise)

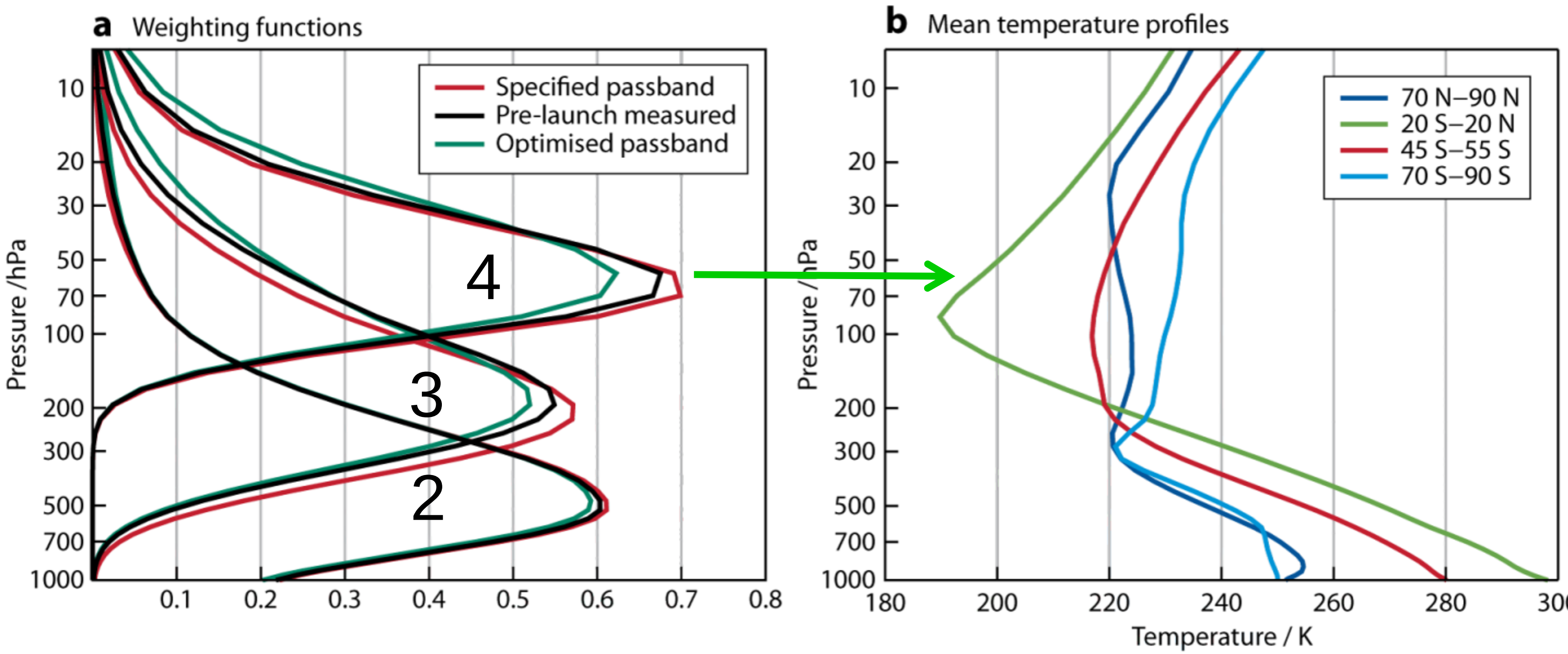
FY-3A MWTS & AMSU-A channels



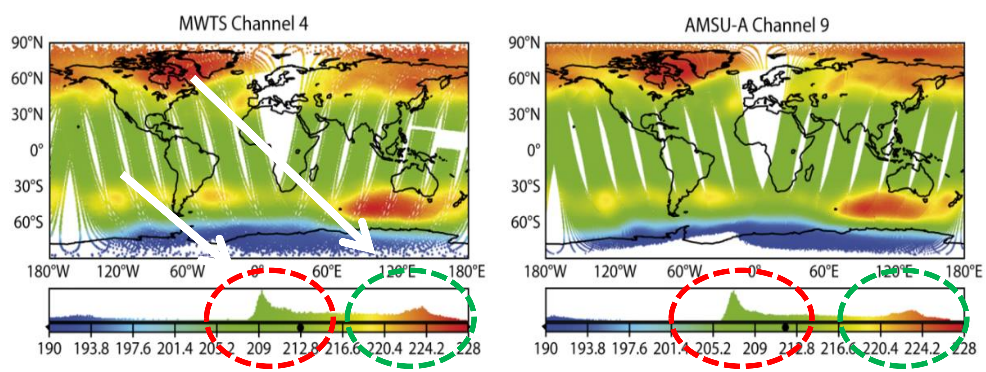
- FY-3 & AMSU-A are heterodyne radiometers
- FY-3: 4 channels. free running LOs
- AMSU-A:14 channels.
  - channels 9 ⇧ phase locked
  - channels 1-8 free running
- Channels < 57 GHz . BW ~ 300 MHz

Peubey and Bell, JTECH, 2014

FY-3A MWTS

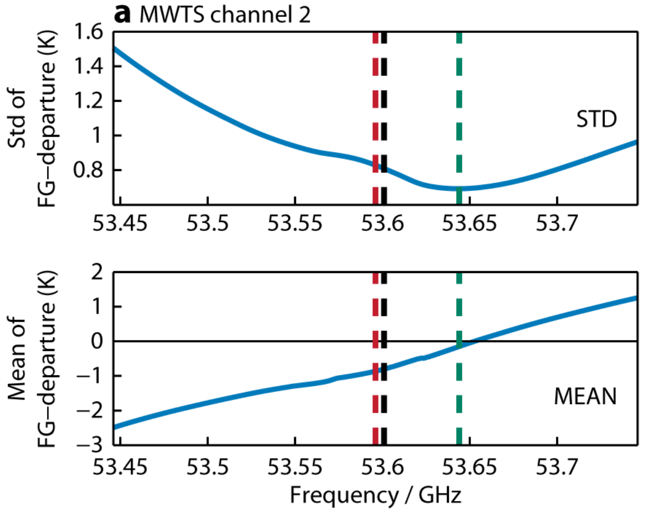


a Weighting functions
Specified passband
Pre-launch measured
Optimised passband
Pressure /hPa
4
3
2
b Mean temperature profiles
70 N–90 N
20 S–20 N
45 S–55 S
70 S–90 S
Temperature / K

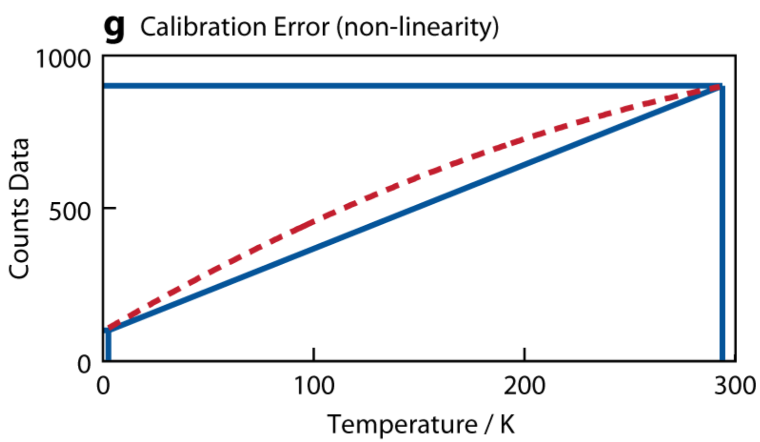


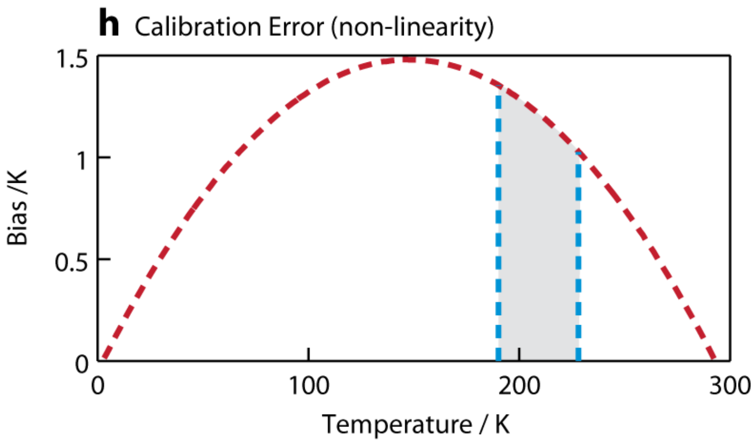
MWTS Channel 4
AMSU-A Channel 9

Optimisation of pass band centre frequency estimates



MWTS Radiometer Non-linearity

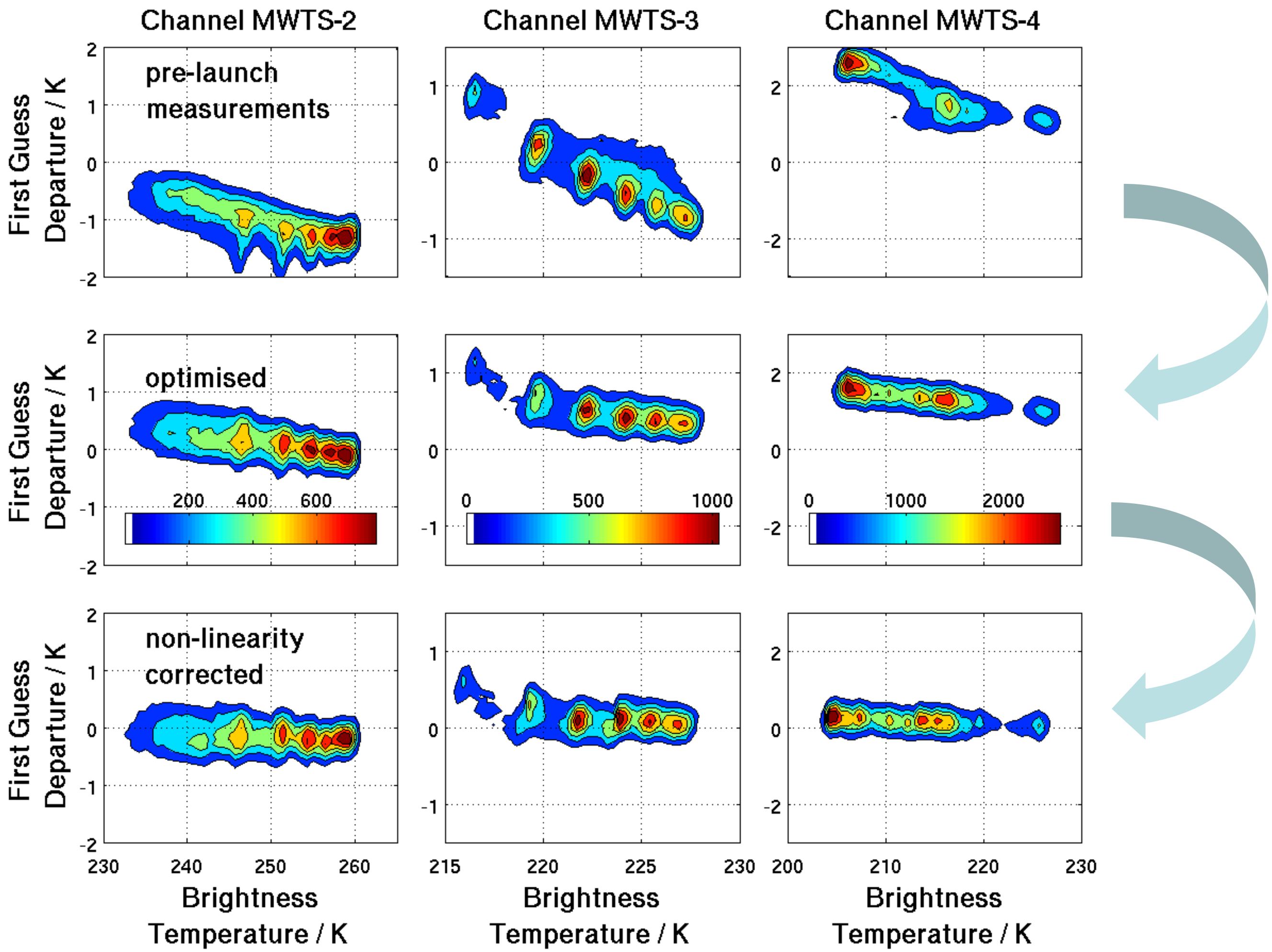




In general the response of a MW radiometer will be slightly non-linear wrt the measured scene temperature.

If perfect linearity is assumed between the 2 calibration points (cold space and a warm target) then an error (bias) results

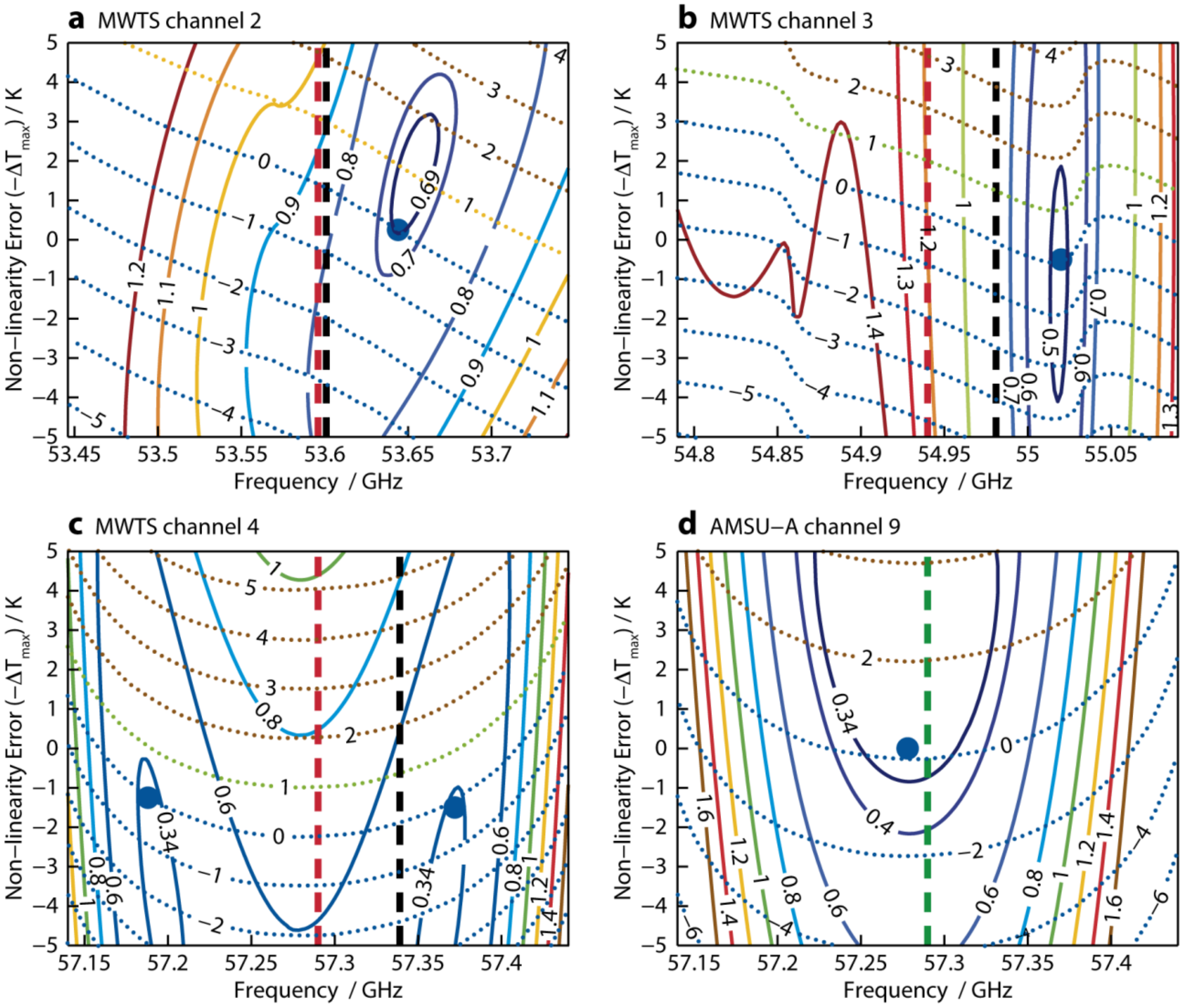
MWTS Radiometer Non-linearity



Adjust passband: variance reduced

Corrected for non-linearity: leaves locally unbiased data

Optimising Estimates of Centre Frequency and ΔT_{MAX}



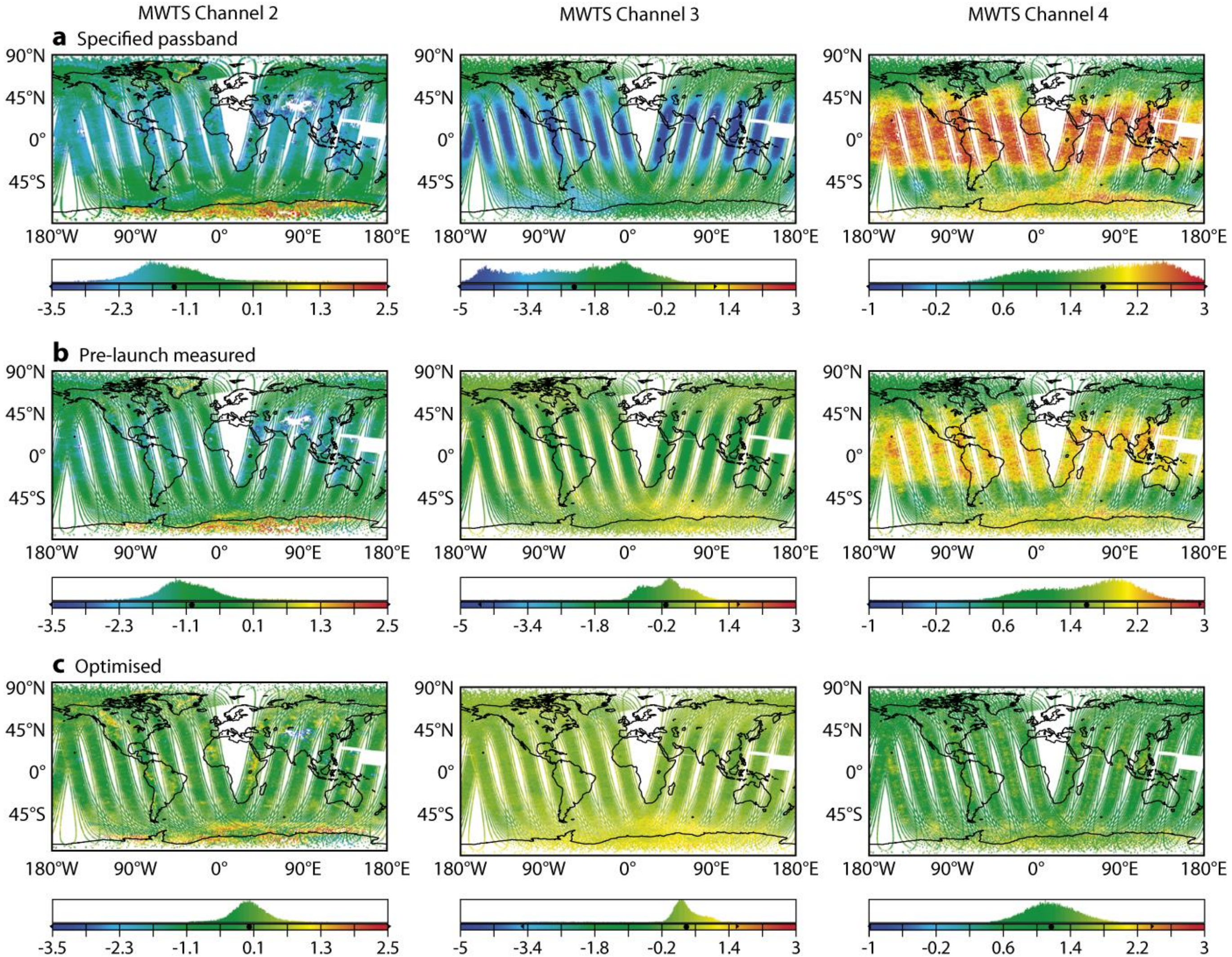
Solid lines represent Contours of std(fg_dep)

Dotted lines represent Contours of mean(fg_dep)

Optimised estimates (spots) obtained from an empirical penalty function

Improved FY-3A MWTS Data Quality

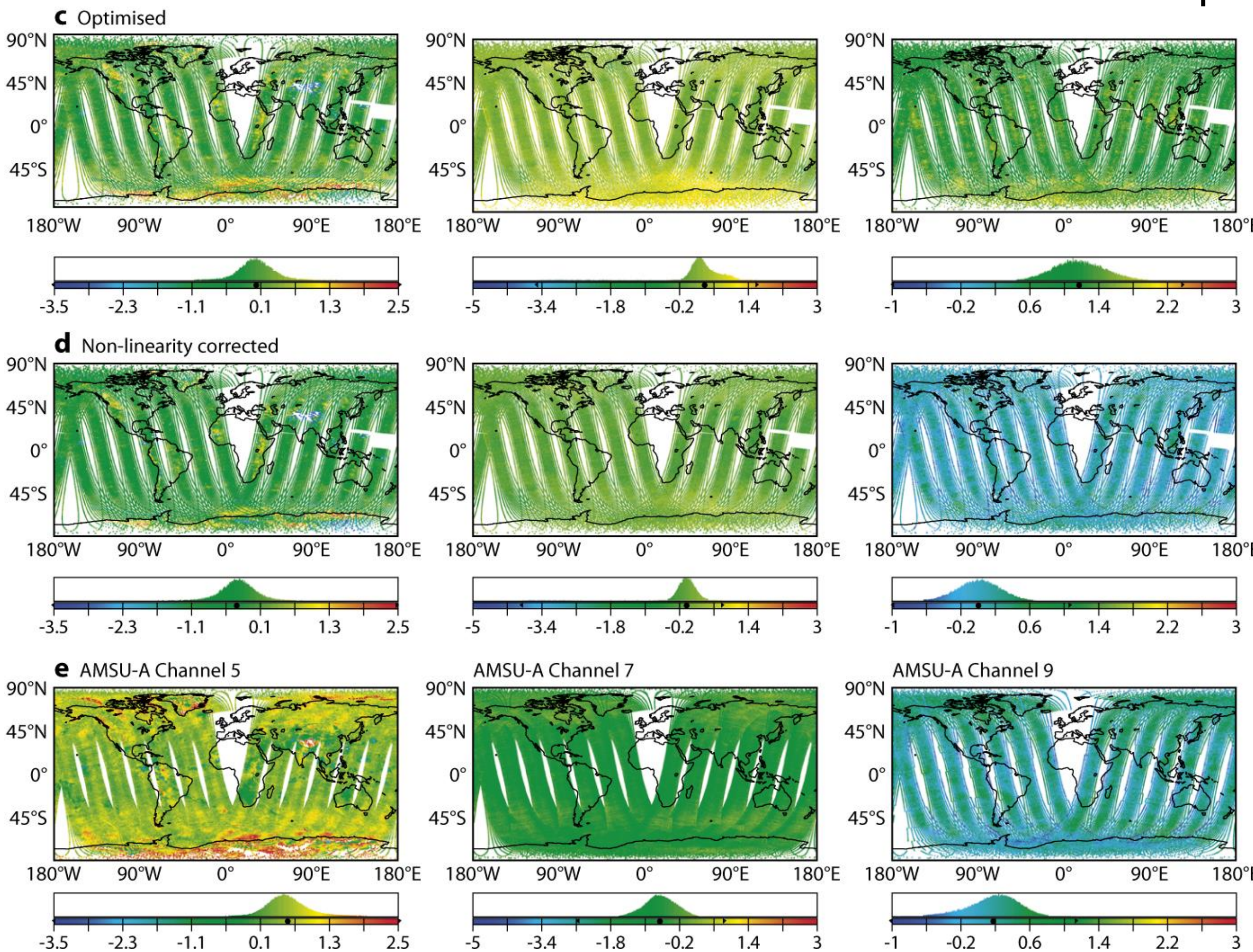
First Guess Departures / K



Improved MWTS Data Quality

Met Office

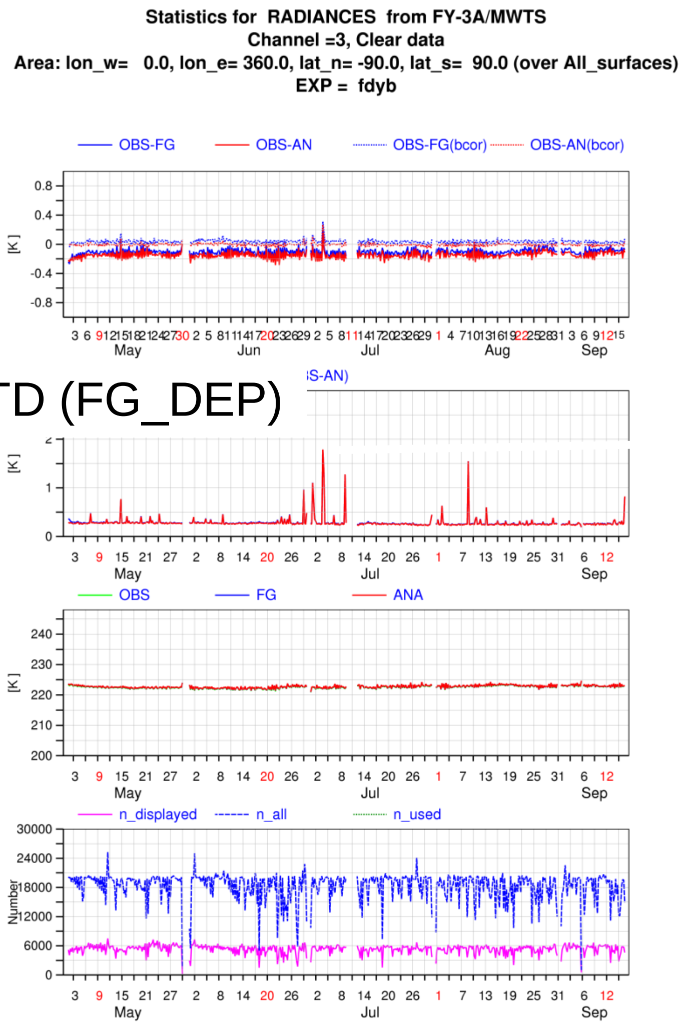
First Guess Departures / K



Lu *et al*, JTECH, 2011 &
ASL, 2012 (NWP impacts)

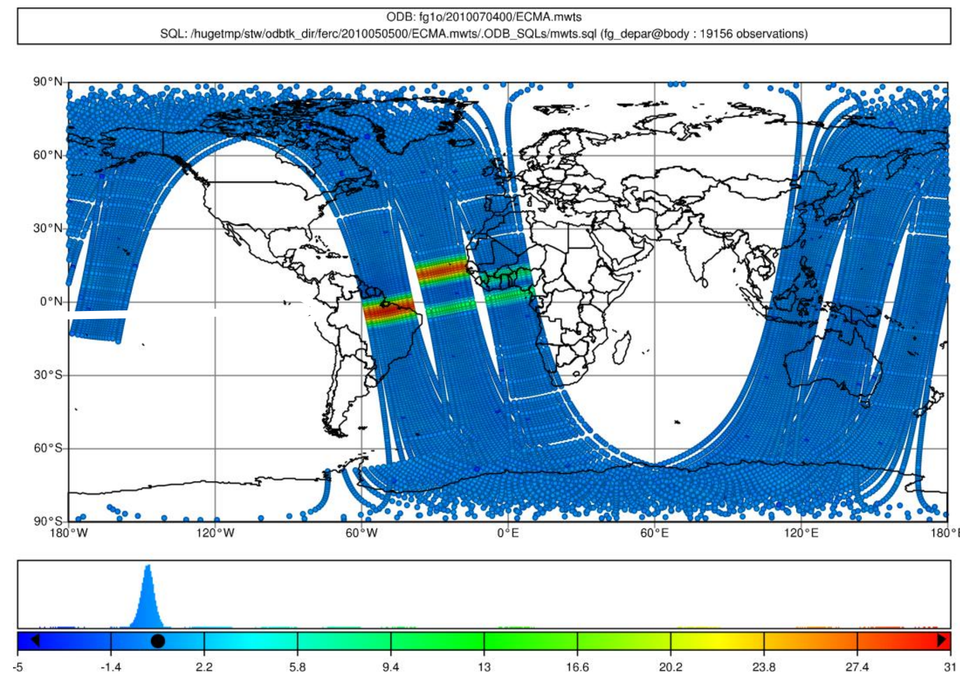
MWTS ‘spikes’ in STD(FG_DEP)

MWTS-3



STD (FG_DEP)

MWTS-3 FG DEPARTURES

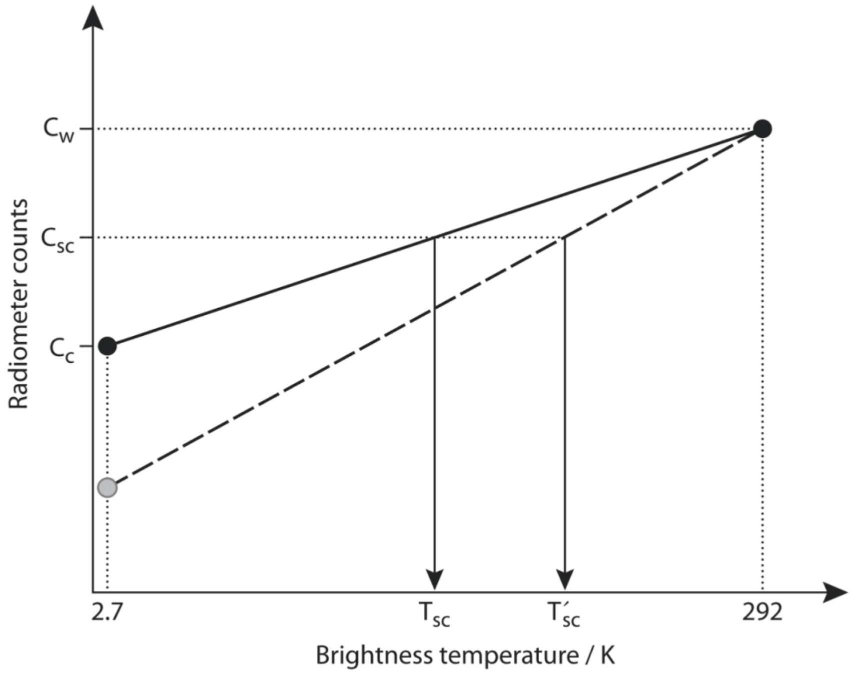


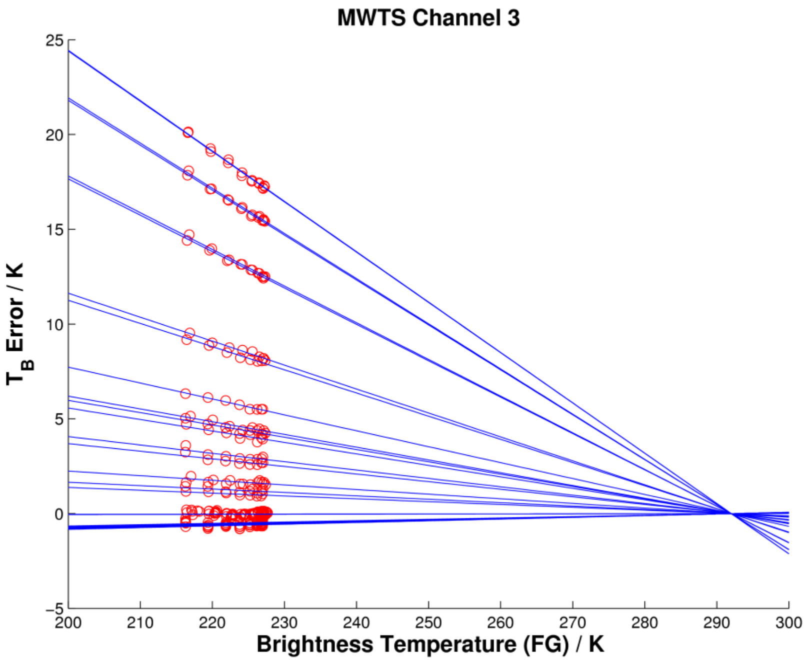
-5K

31K

MWTS 'spikes' in STD(FG_DEP): Cold space counts errors

An error caused by cold space *drop-outs* would be expected to lead to an error which tends to 0 as T_{SCENE} tends to the warm target temperature



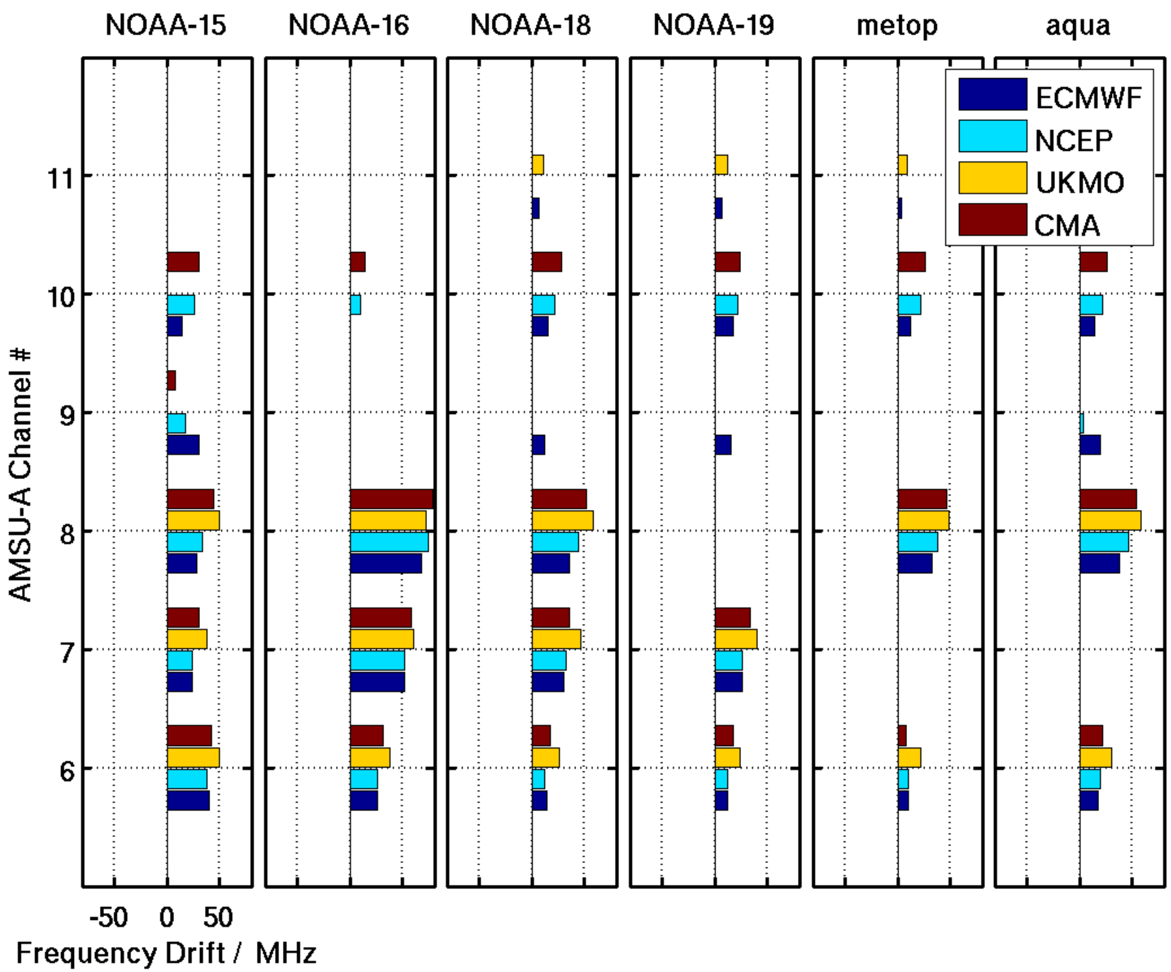


35 of 37 events during May - Sept 2010 are cold space drop outs

Post-launch characterisation using NWP

- **SSMIS** - reflector emission, warm load intrusions
- **TMI – reflector emission**
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A**: pass band shifts and drifts
- **ATMS**: striping (1/f calibration noise)

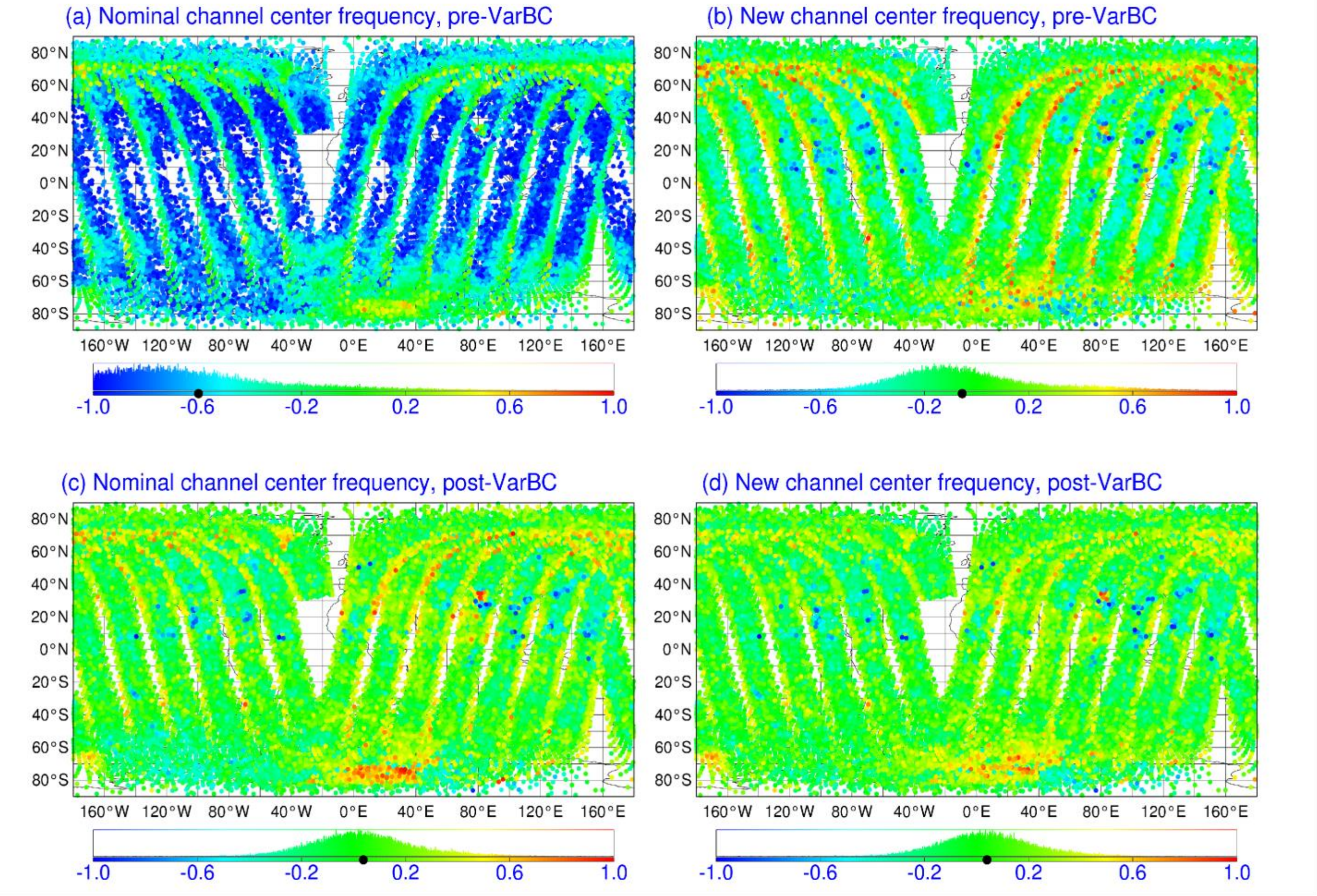
Analysed Frequency Shifts for AMSU-A: NWP Model Dependence



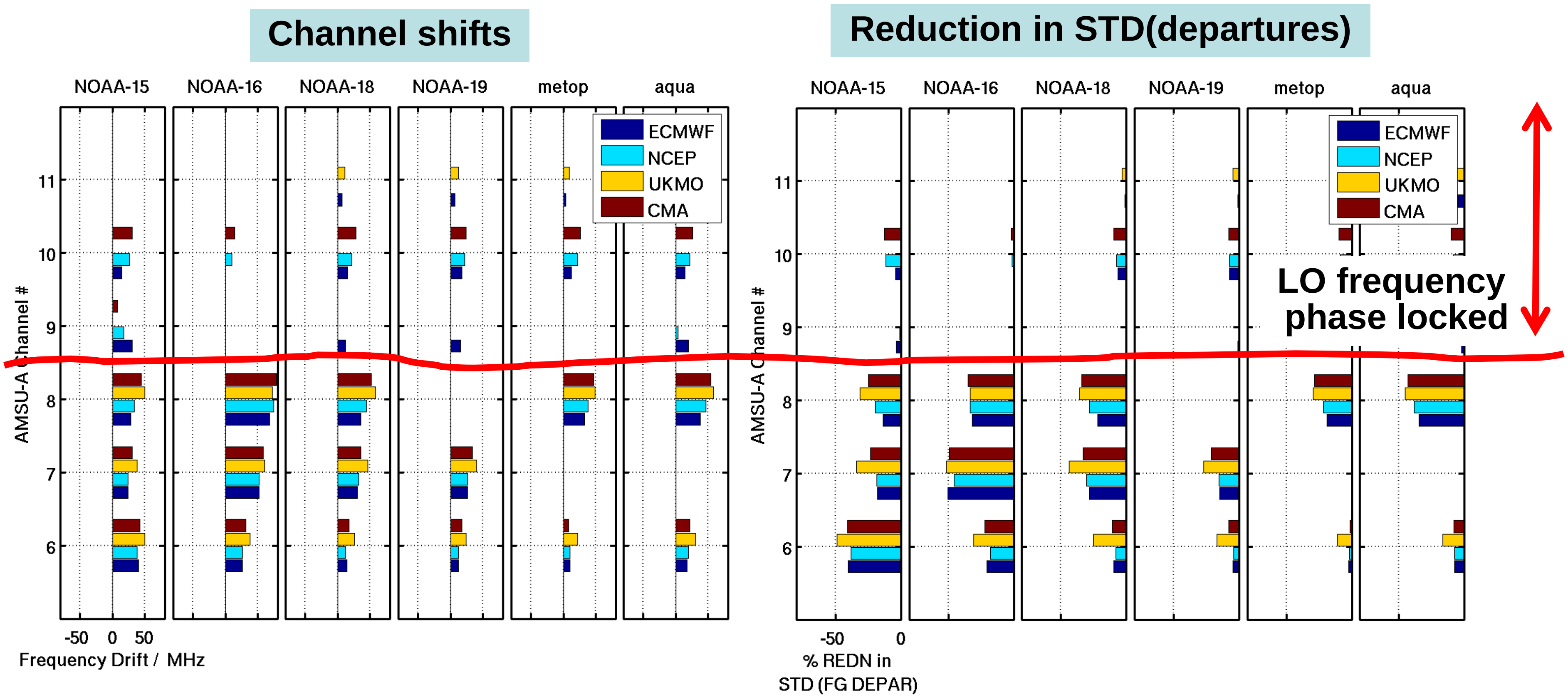
Similar results obtained From 4 NWP models (ECMWF, UKMO, NCEP, CMA)

Lu and Bell, JTECH, 2014

Frequency Shifts for AMSU-A: e.g. NOAA-16 Channel 6

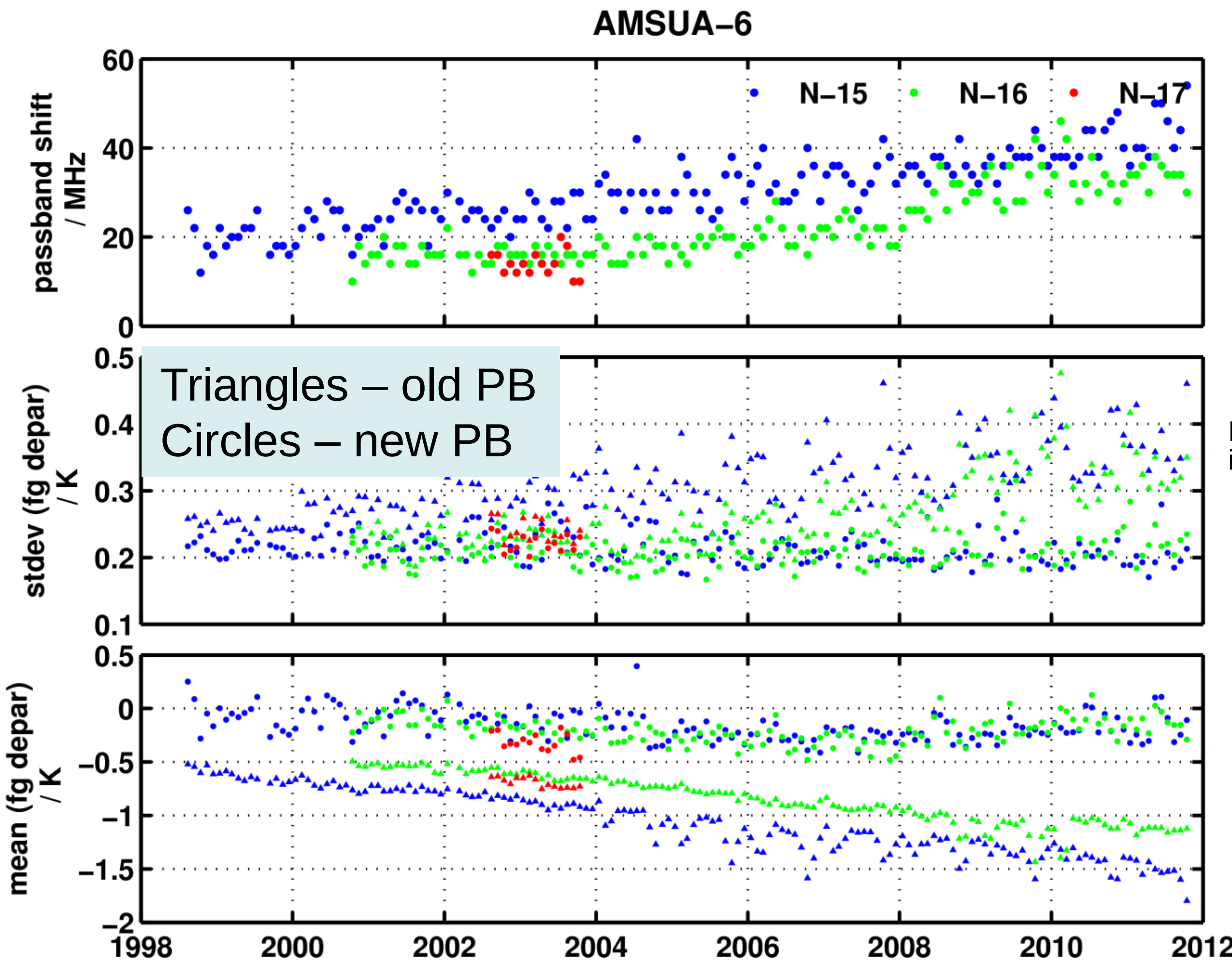


Analysed Frequency Shifts for AMSU-A: NWP Model Dependence



Frequency shifts with time
e.g. AMSU-6 (NOAA-15,-16,-17)

Met Office

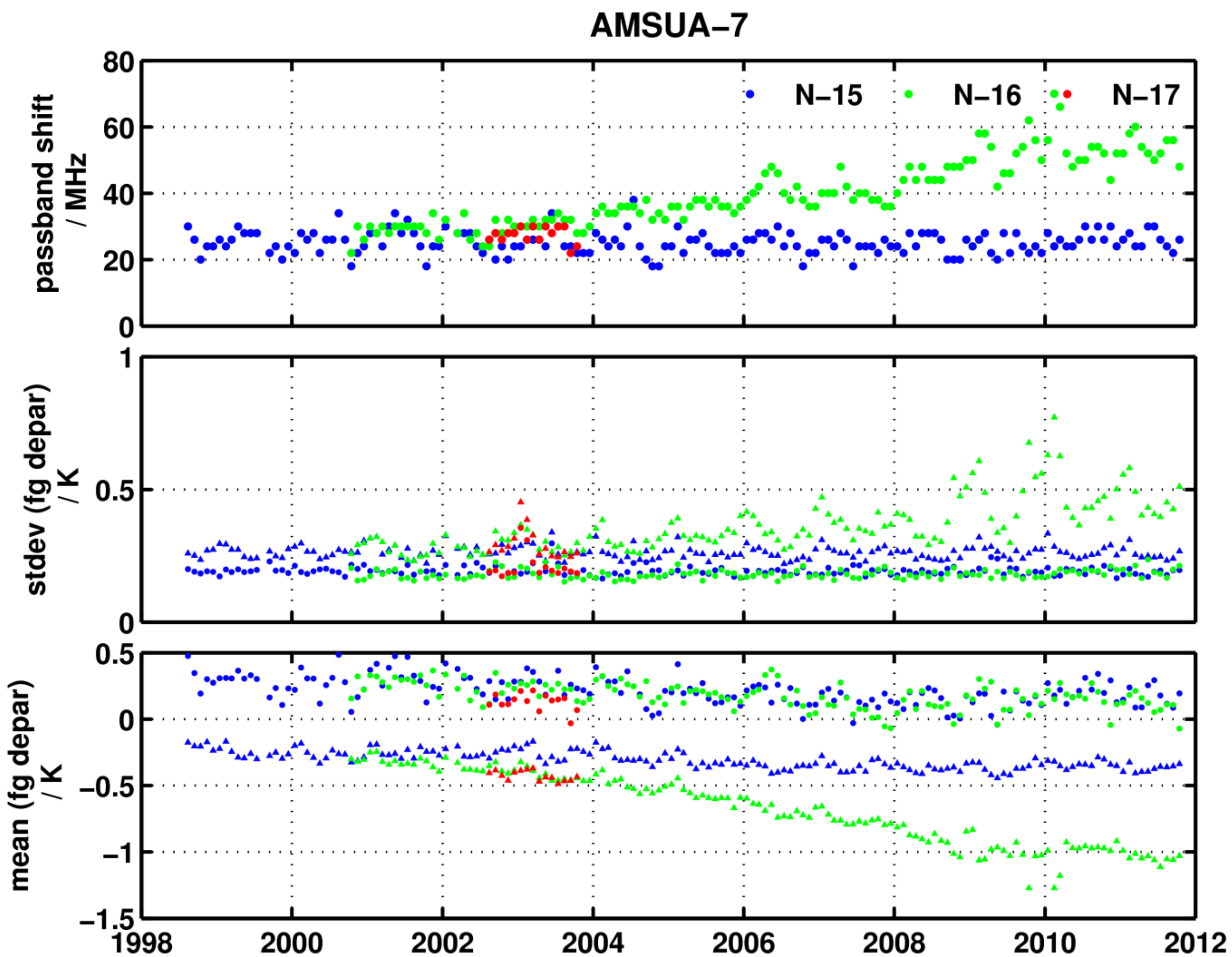


Uses ERA-Interim analysis fields

Reduced seasonal cycle in obs-model misfit

Reduced inter-satellite biases & obs-model biases

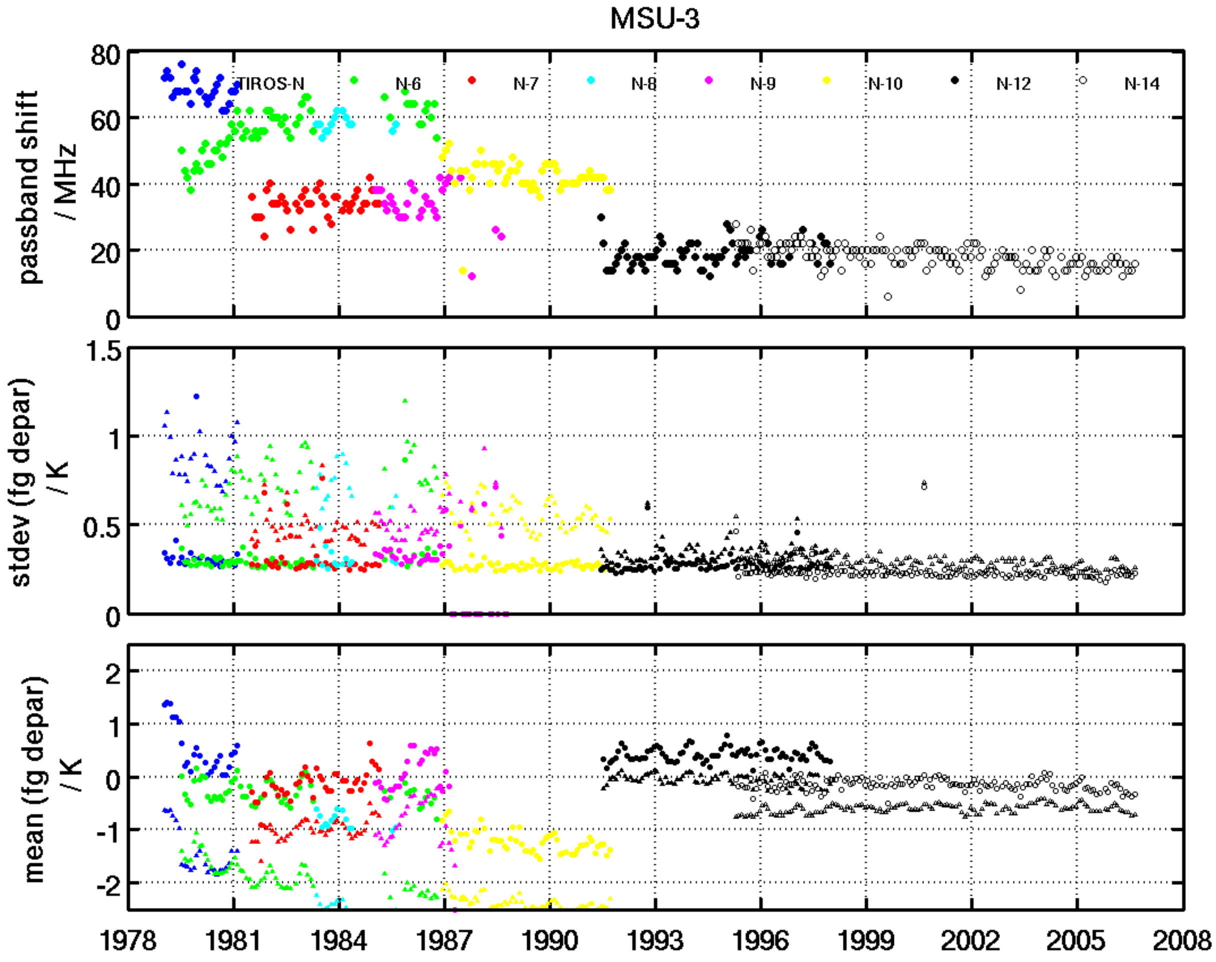
Frequency shifts with time
e.g. AMSU-7 (NOAA-15,-16,-17)



Reduced seasonal cycle in obs - model misfit

Reduced inter-satellite biases & obs-model biases

Analysed Frequency Shifts for MSU : Time Dependence (Channel 3)



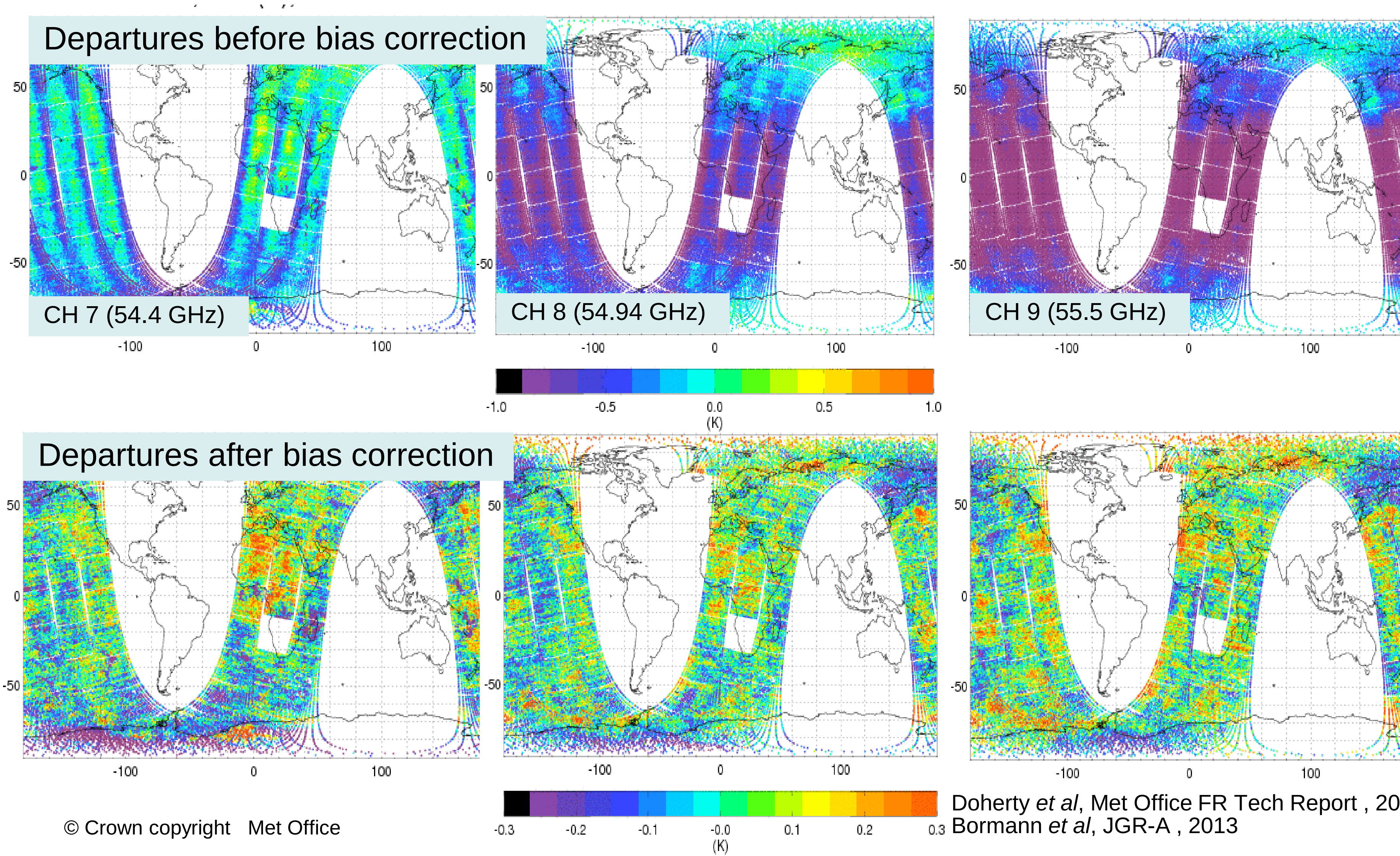
Large offsets for all satellites, earlier satellites worse

Accounting for passband shifts significantly improves fg departure statistics (mean and standard deviation.

Post-launch characterisation using NWP

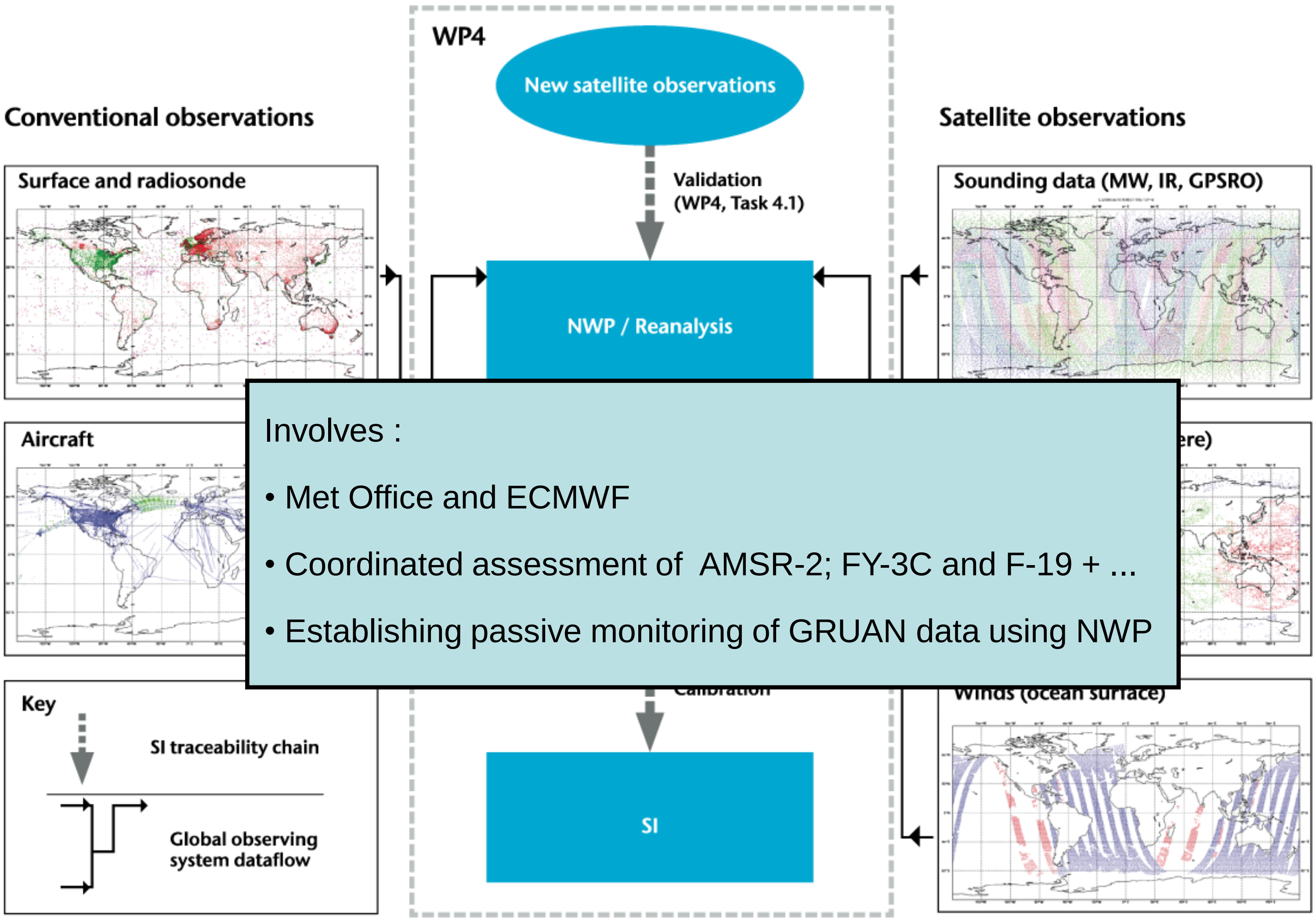
- **SSMIS** - reflector emission, warm load intrusions
- **TMI** – reflector emission
- **FY-3A** – pass band uncertainties, radiometer non-linearities, and transient processing issues
- **MSU-AMSU-A**: pass band shifts and drifts
- **ATMS**: striping (1/f calibration noise) and reflector emission

S-NPP ATMS
Striping and reflector emission



Doherty *et al*, Met Office FR Tech Report , 2013
Bormann *et al*, JGR-A , 2013

GAIA-CLIM



Involves :

- Met Office and ECMWF
- Coordinated assessment of AMSR-2; FY-3C and F-19 + ...
- Establishing passive monitoring of GRUAN data using NWP

Conclusions & Future Work

- NWP, reanalysis and climate applications generate increasingly demanding requirements on satellite measurements
- NWP provides a very powerful tool for the assessment of satellite measurements – complementing alternative approaches
- It's a good working assumption that **all** radiometers will exhibit unique bias characteristics & that bias correction schemes may have to cope with a wide range of effects
- More work needed on : MSU, AMSU-A, FY-3C , SSMIS, ...
- We don't really know what harm *residual* biases are causing in NWP & Reanalysis systems. More work needed here !
- Risks of sub-optimal instrument performance can be mitigated through closer links between instrument teams and end-users (S-NPP being a very good example) – though direct collaboration; science advisory groups & Cal/Val programs. Instrument specifications don't capture the full picture !

The end.

Thanks for listening !

MWTS Frequency Shift: An Explanation ?

Errors in pre-launch frequency measurement ?

(Note: shift we estimate is 30 – 50 MHz in 53 GHz *ie* ~ (6-10) in 10^4)

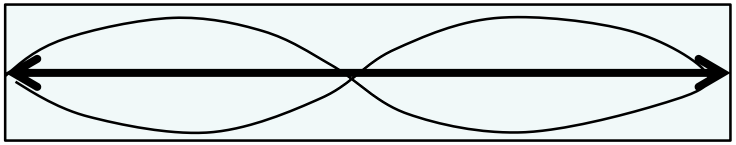
<u>No !</u> : U(ω) < 1 part in 10^{10} , *ie* ~ 5 Hz

but ….

Gunn diode oscillator frequency (ω_n) determined by resonant modes (n) of a cavity:

$$\omega_n = \frac{nc}{2l\mu}$$

(Essen & Froome, 1952)



length l, refractive index μ

$\mu_{AIR} = 1 + 2.88 \times 10^{-4}$

$\mu_{SPACE} = 1$

Channel	Estimated shift (relative to pre-launch) / MHz	Rescaled (relative to pre-launch) / MHz (from manufacturer)
2	**55.0 ± 2.5**	**32.0**
3	**39.0 ± 2.5**	**32.0**
4	**32.0 ± 2.5**	**33.0**

AMSU-A1 block diagram

- Architecture is common to all versions of AMSU-A1
  - some changes in component technologies have been implemented
- Ch 3-15 all use double-sideband heterodyne (mixer + LO) configuration
  - Ch 3-10 & 15 have two RF passbands
  - Ch 11-14 use sub-banding to provide four RF passbands each
- Note channels 3,4 5 and 8 illuminates a different reflector -