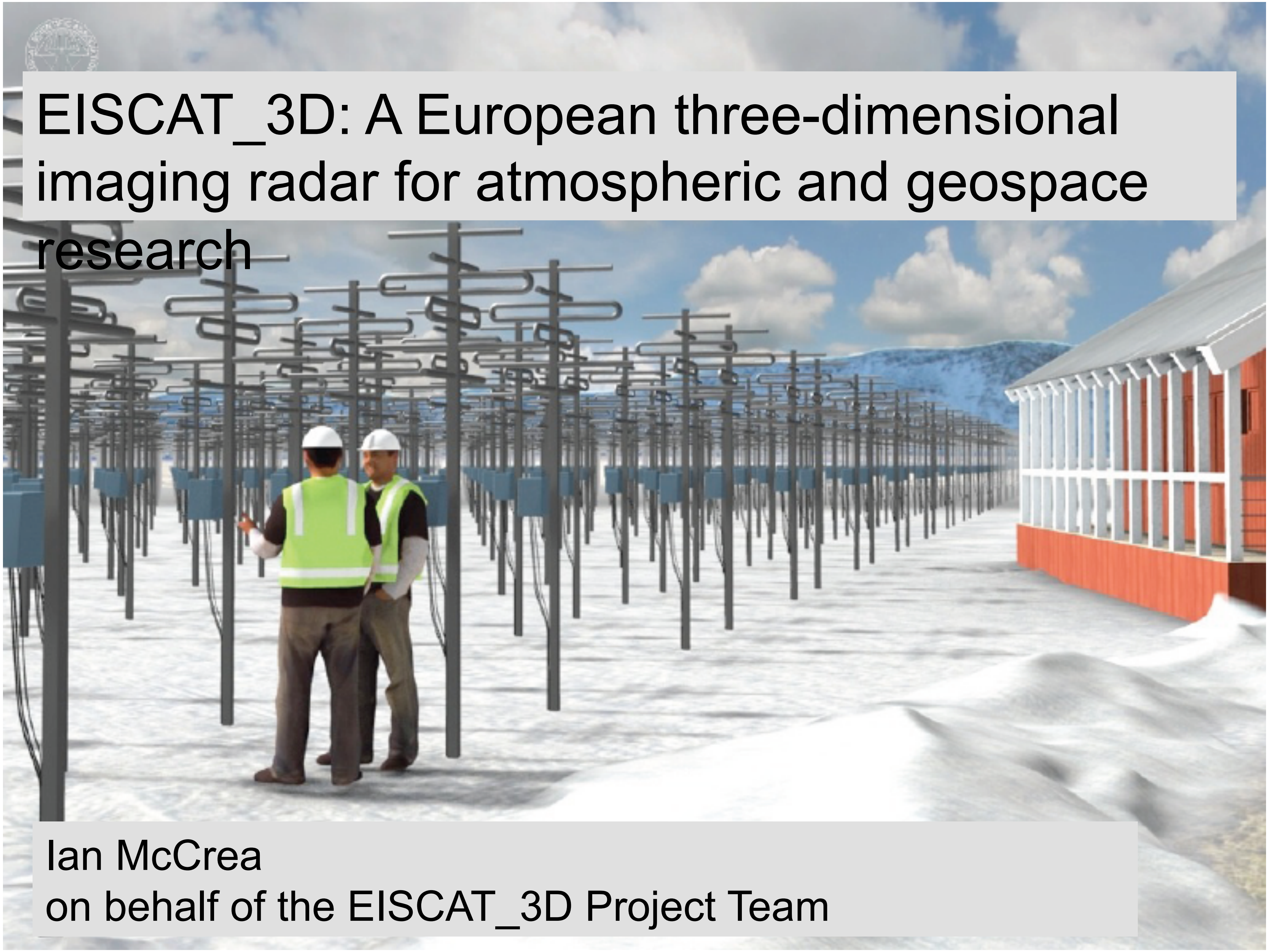
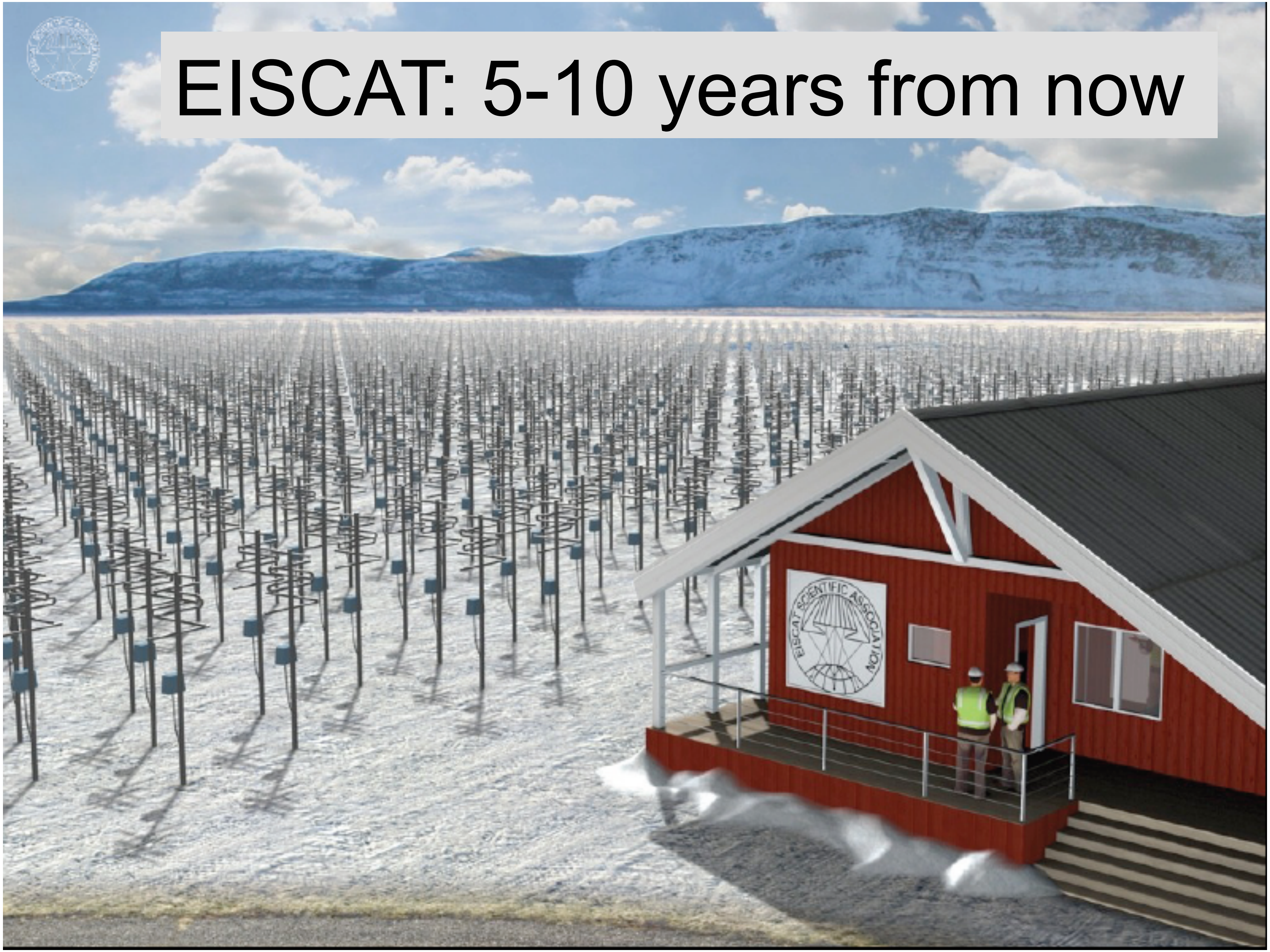
EISCAT_3D: A European three-dimensional imaging radar for atmospheric and geospace research

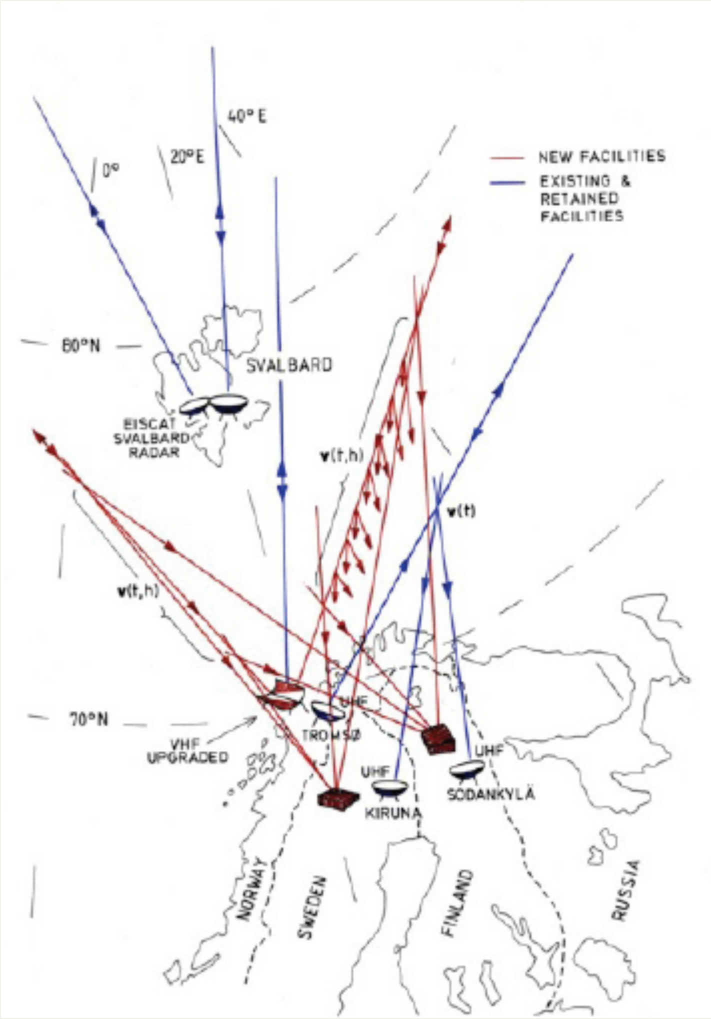


Ian McCrea
on behalf of the EISCAT_3D Project Team

EISCAT: 5-10 years from now



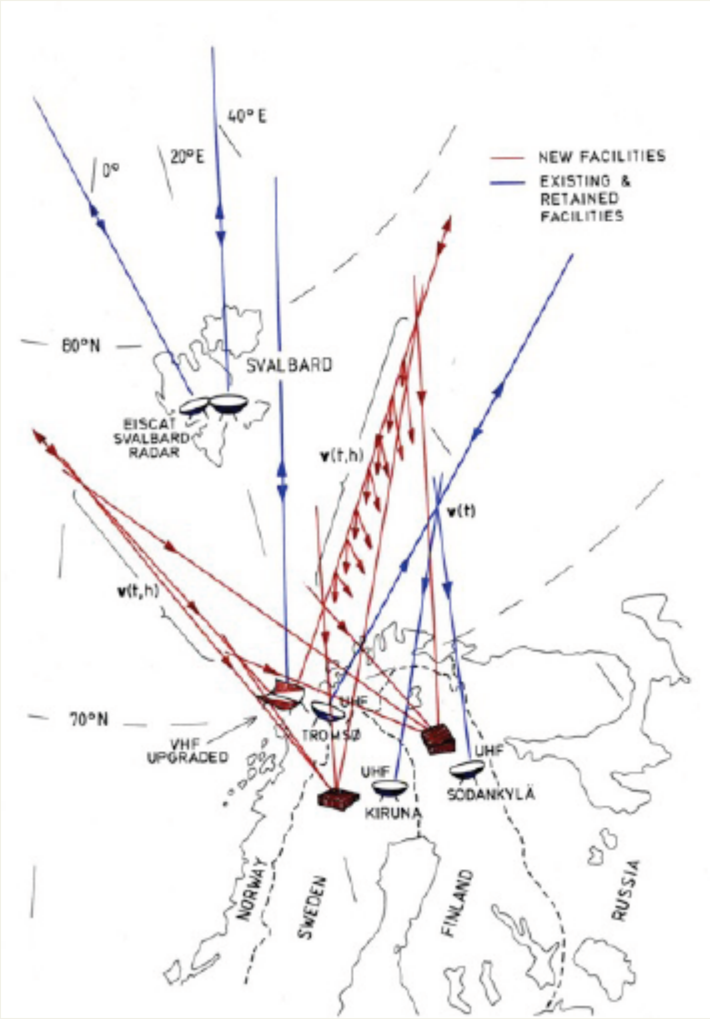
The EISCAT_3D Concept



•Replace mainland system with multi-static phased array system, comprising both transmit/receive and passive array

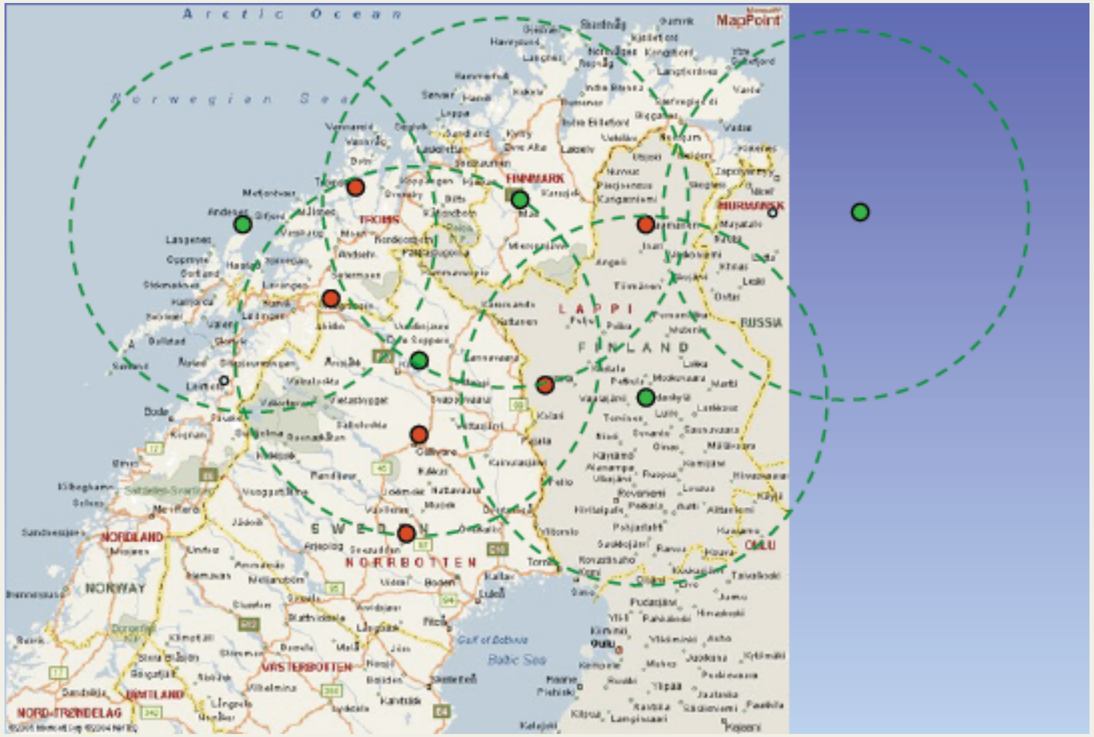
•Integrated multi-beam and imaging capabilities

The EISCAT_3D Concept



•Phased array systems are inherently modular, so we could add arrays (or transmission capability) as funding becomes available

•At this stage, we should be thinking big.....

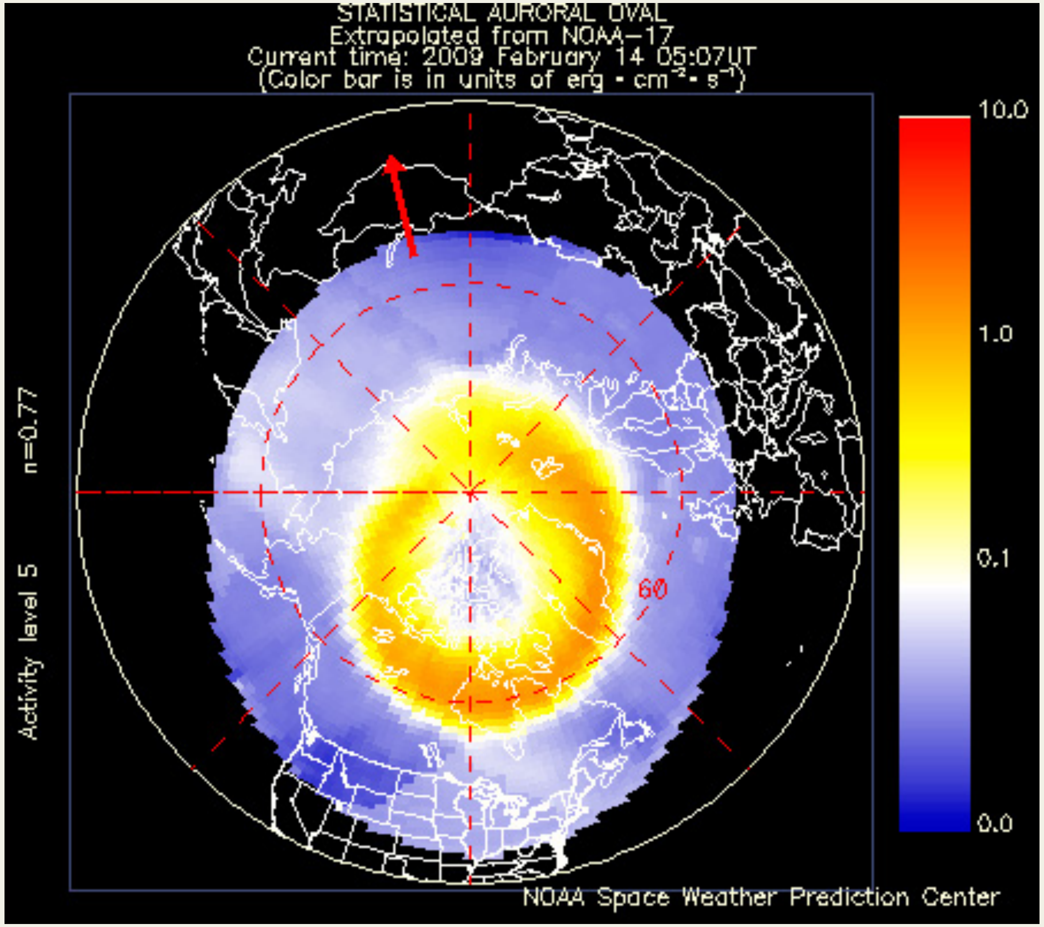


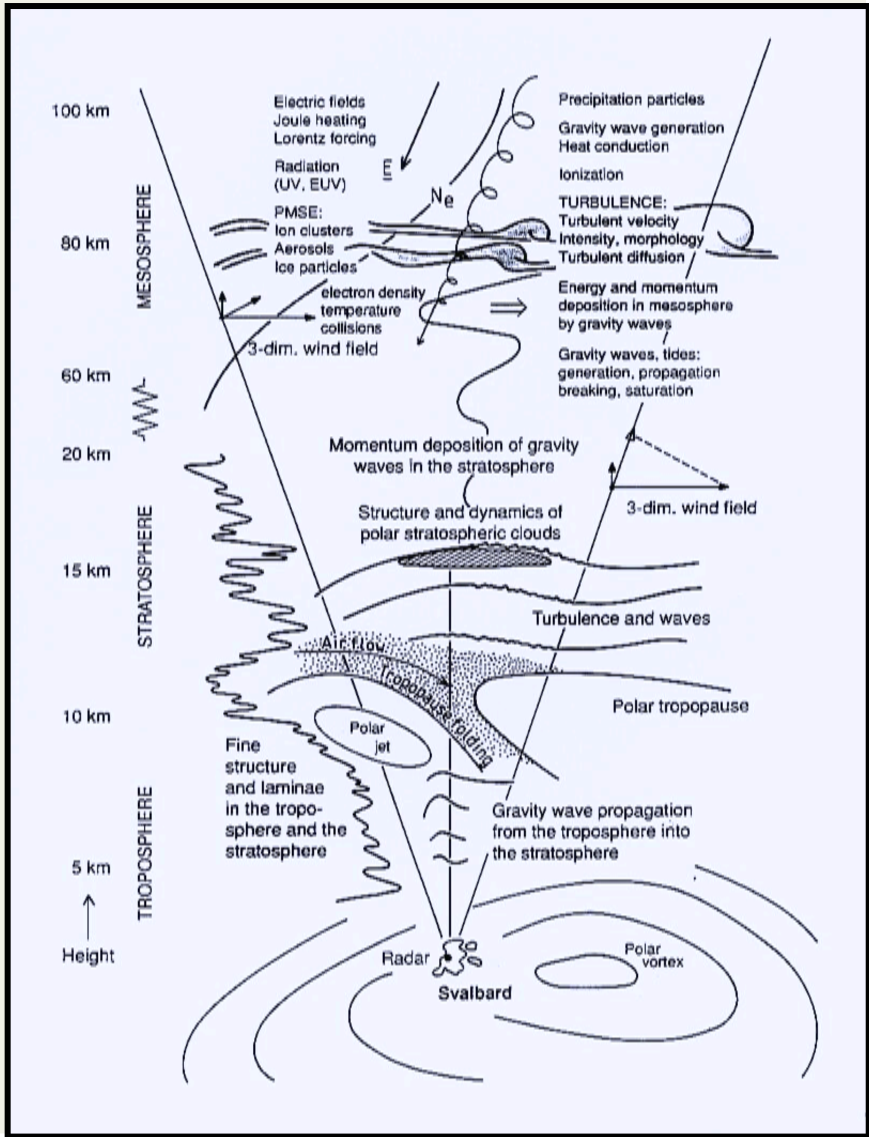
EISCAT_3D: Key Capabilities

- Five key capabilities:
  - Volumetric imaging and tracking
  - Aperture Synthesis imaging
  - Multistatic configuration
  - Greatly improved sensitivity
  - Transmitter flexibility

- These capabilities never before combined in a single radar

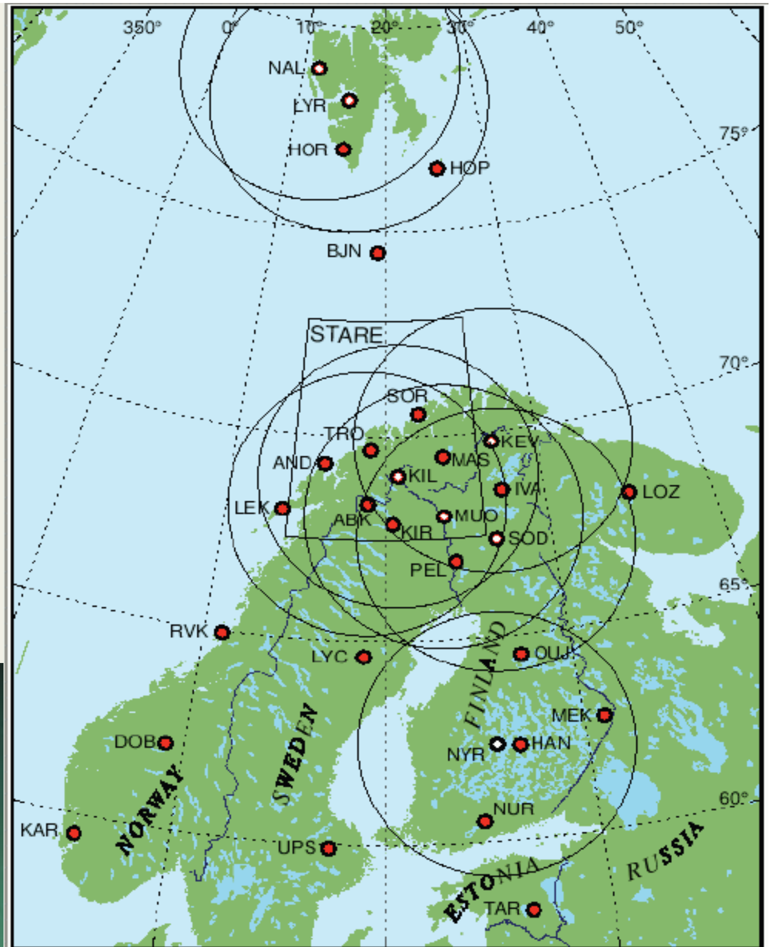
Why our location is special



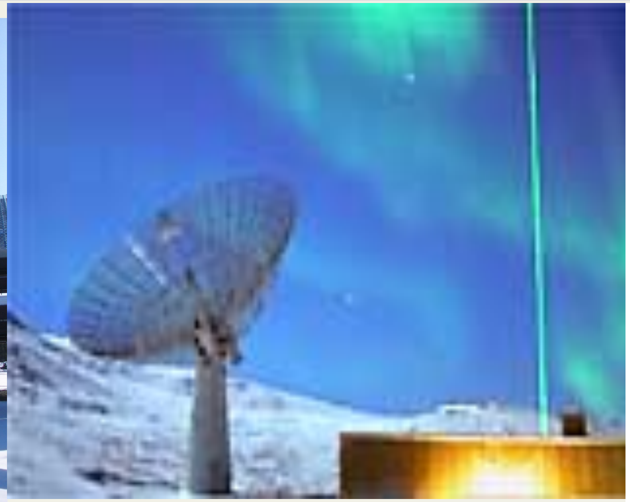


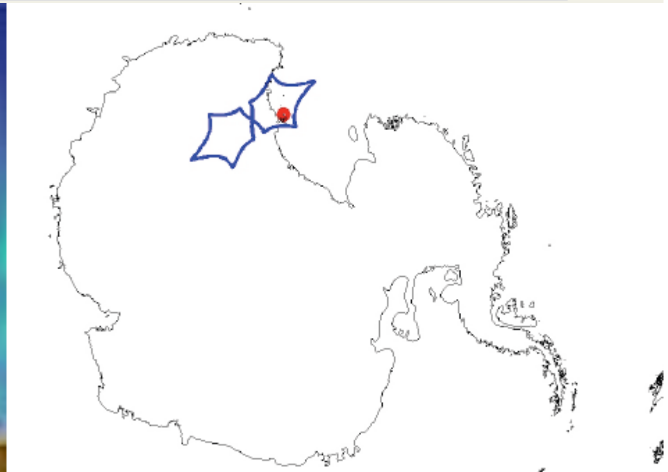
E3D & Everything

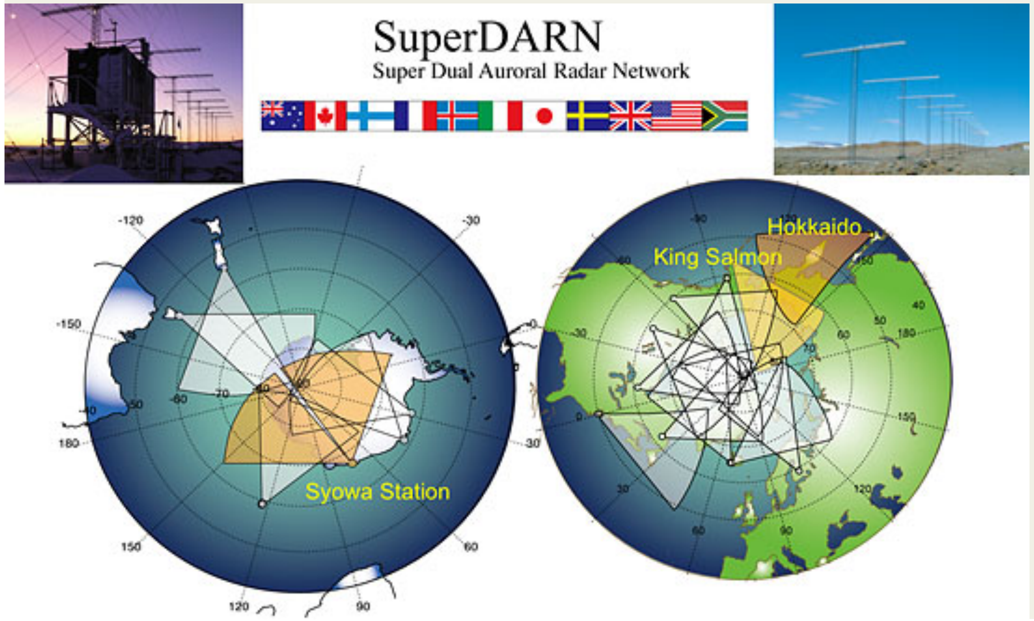
Complementary Fenno-Scandian Infrastructure

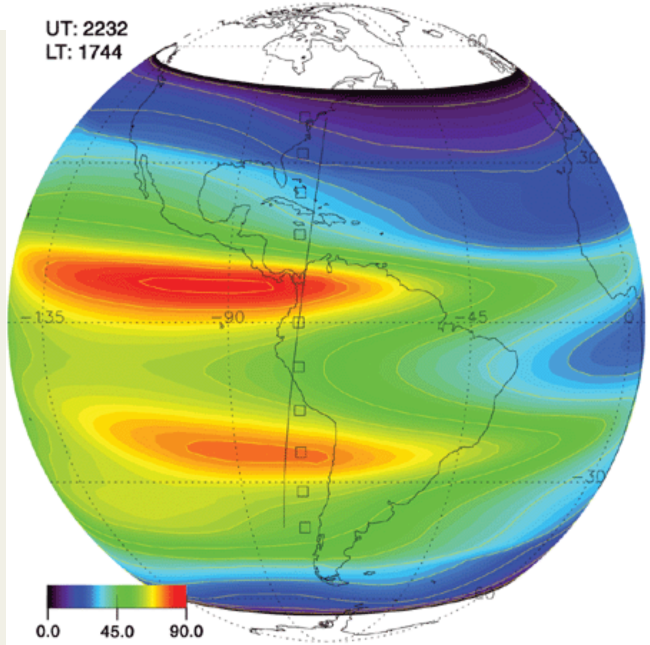


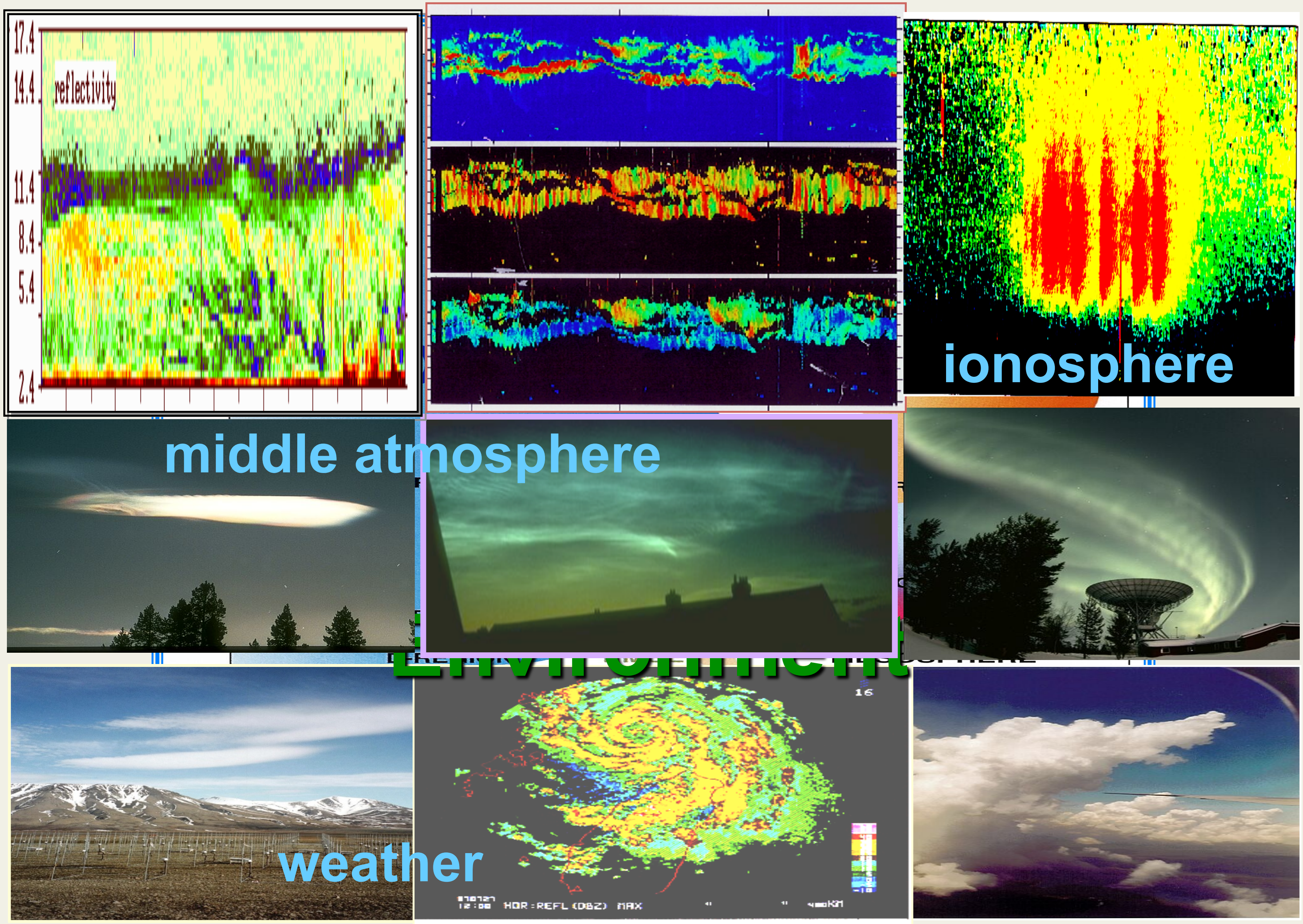
The International Perspective



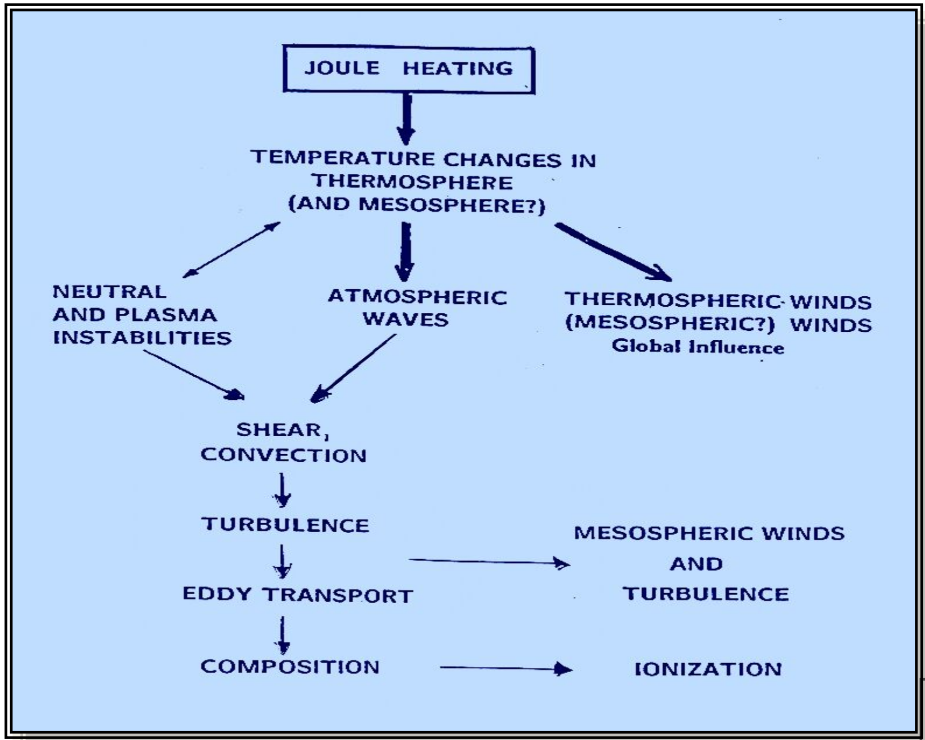


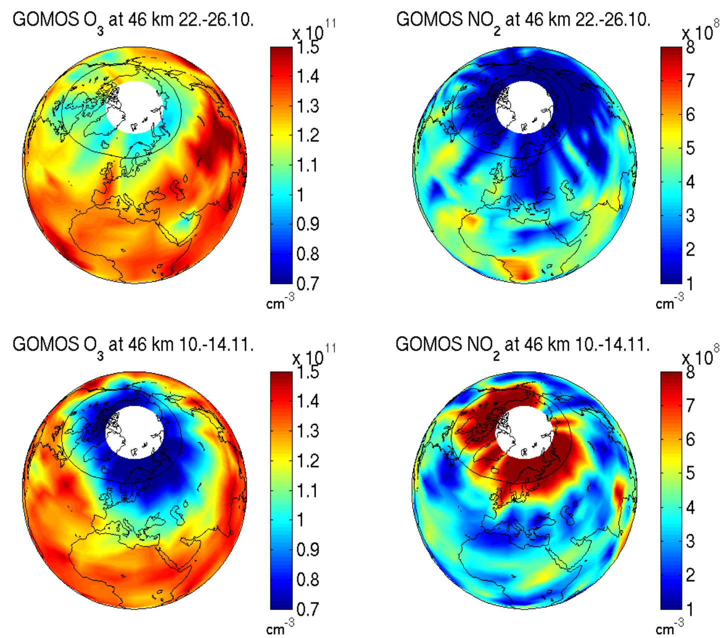


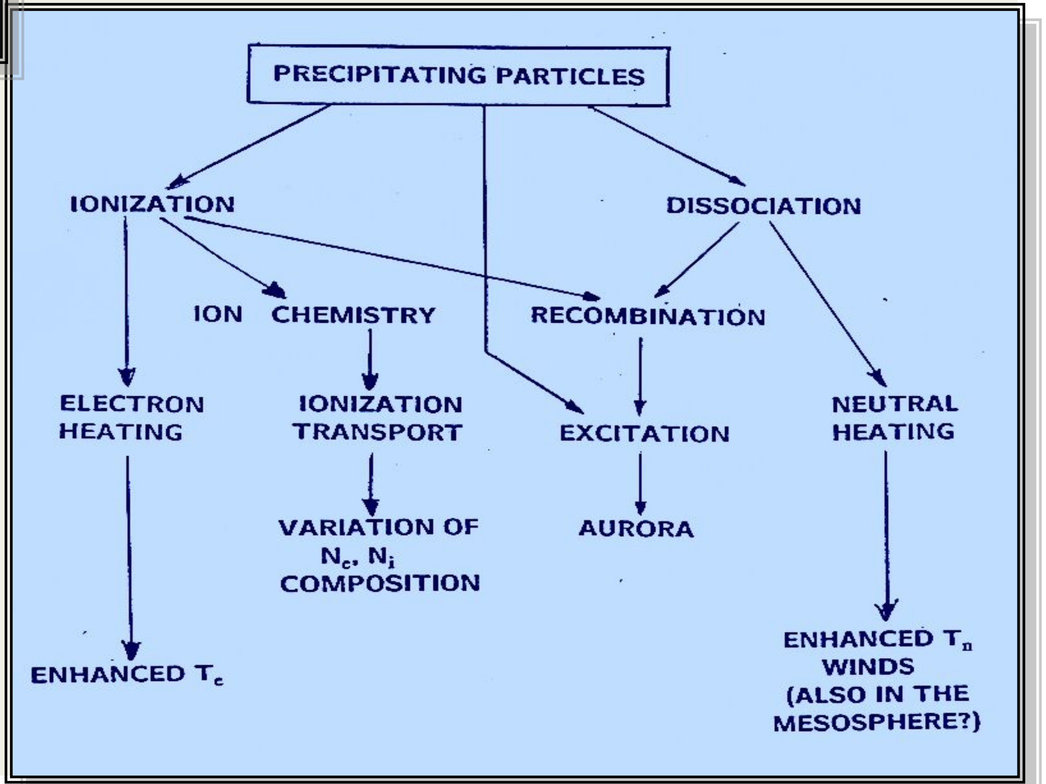



17.4
14.4
reflectivity
11.4
8.4
5.4
2.4
ionosphere
middle atmosphere
Environment
16
weather
HDR:REFL (DBZ) MAX

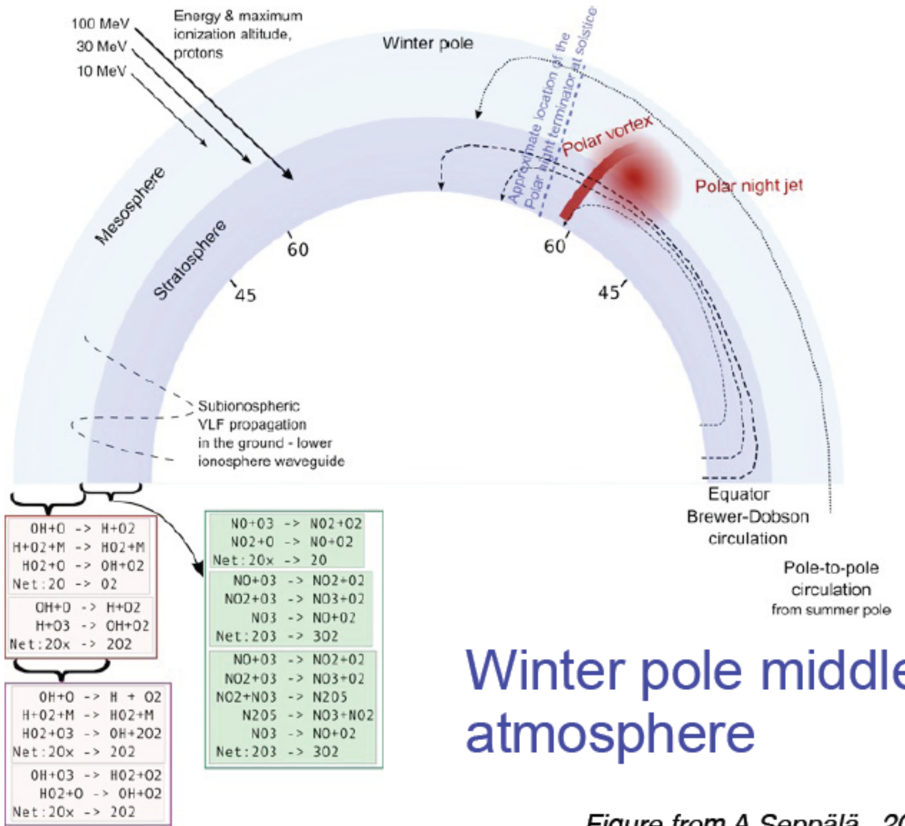
Atmospheric Coupling: Chemistry and Dynamics





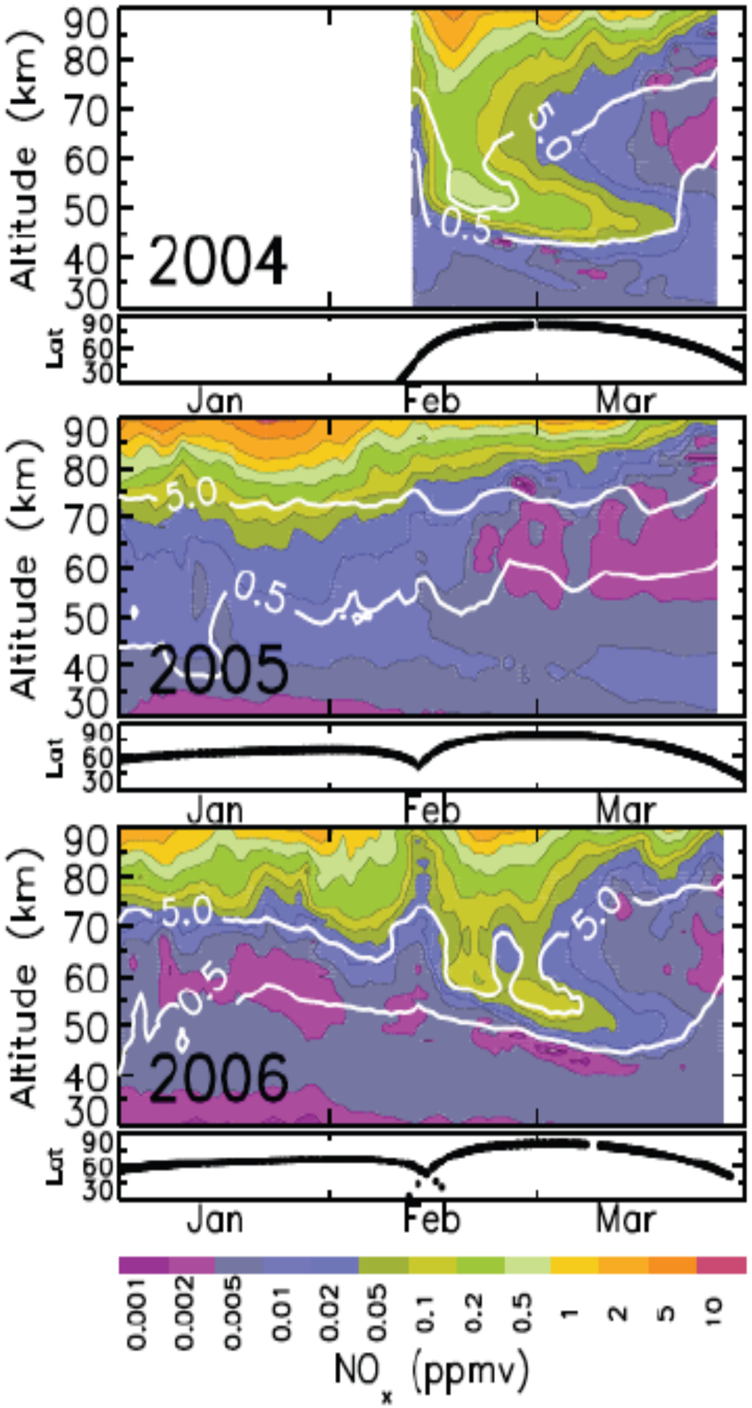


Atmospheric Coupling: The Polar Vortex

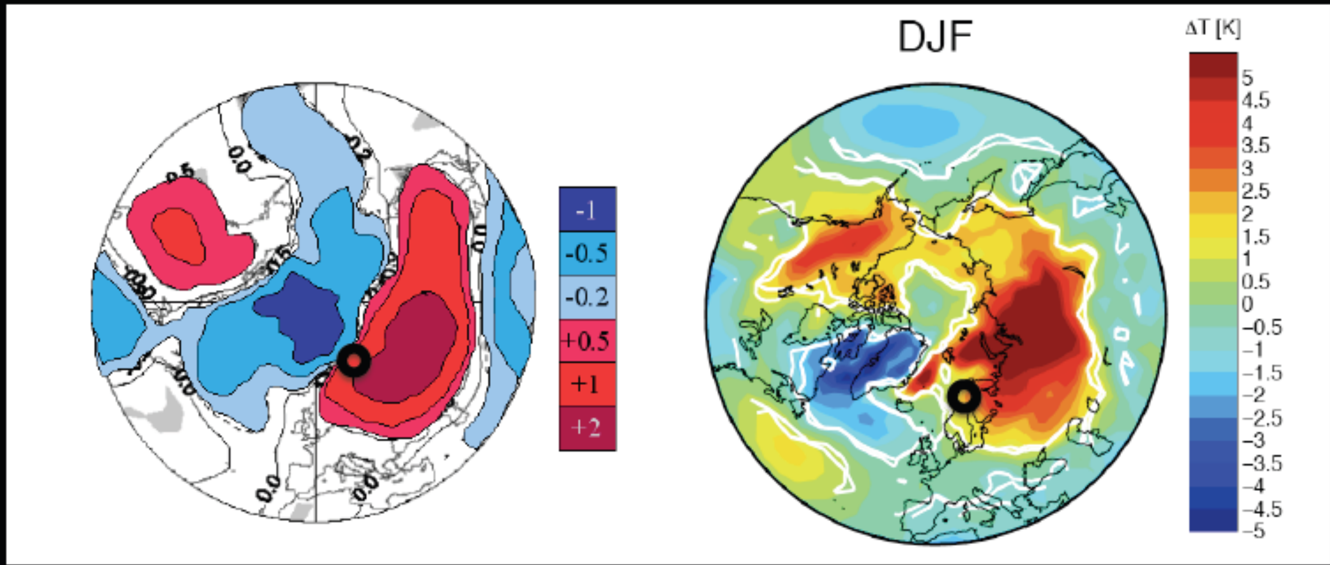


Winter pole middle atmosphere

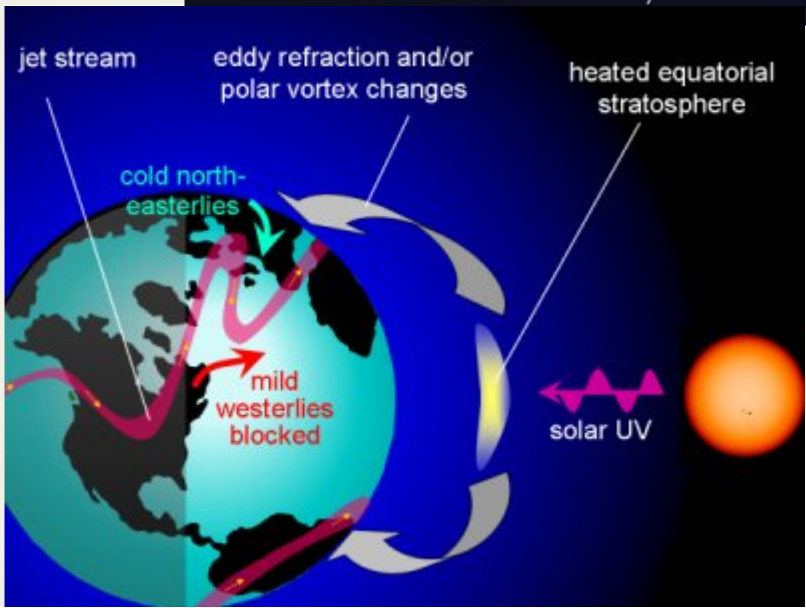
Figure from A.Seppälä , 2007



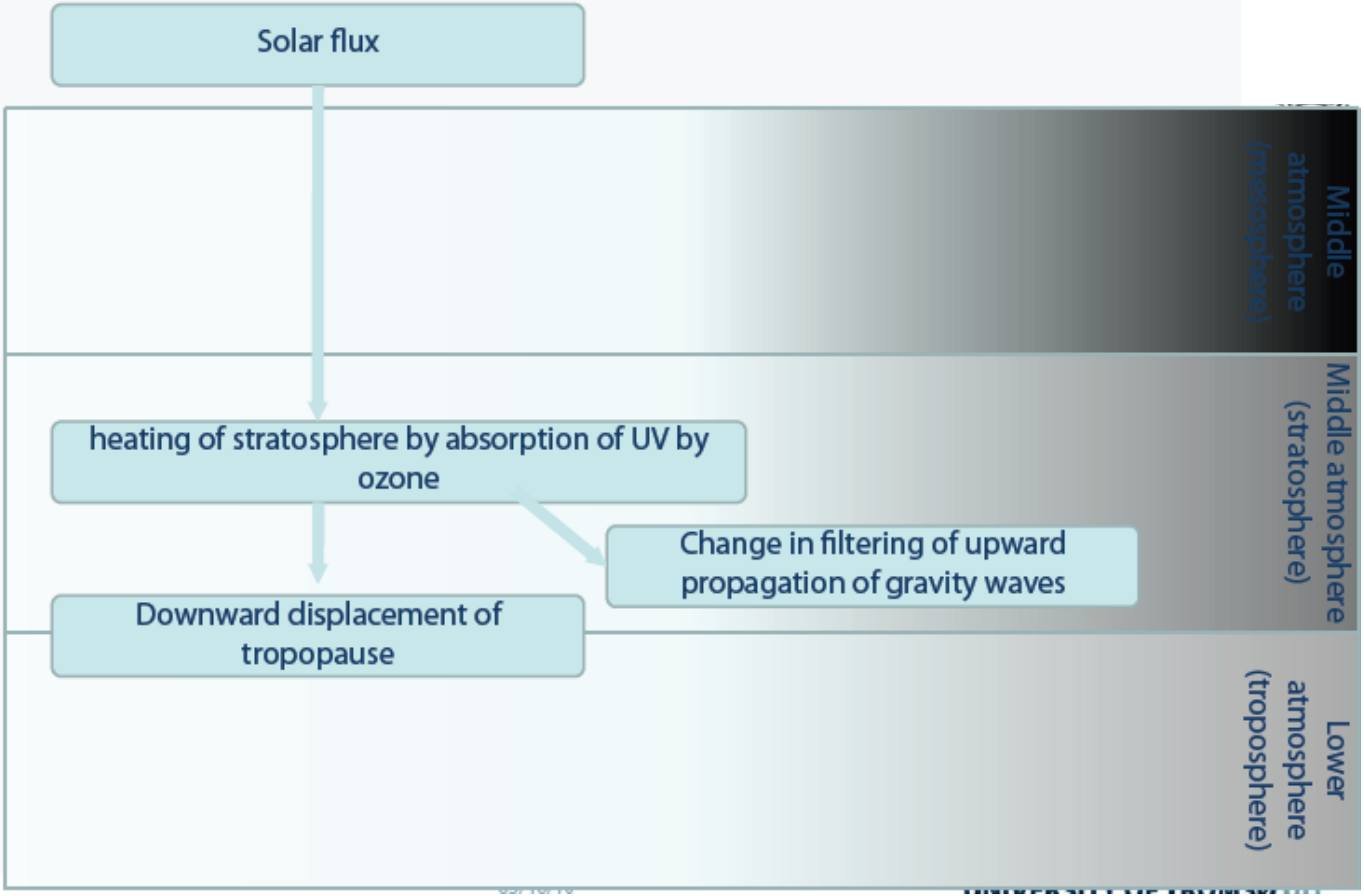
Atmospheric Coupling: Links to Climate



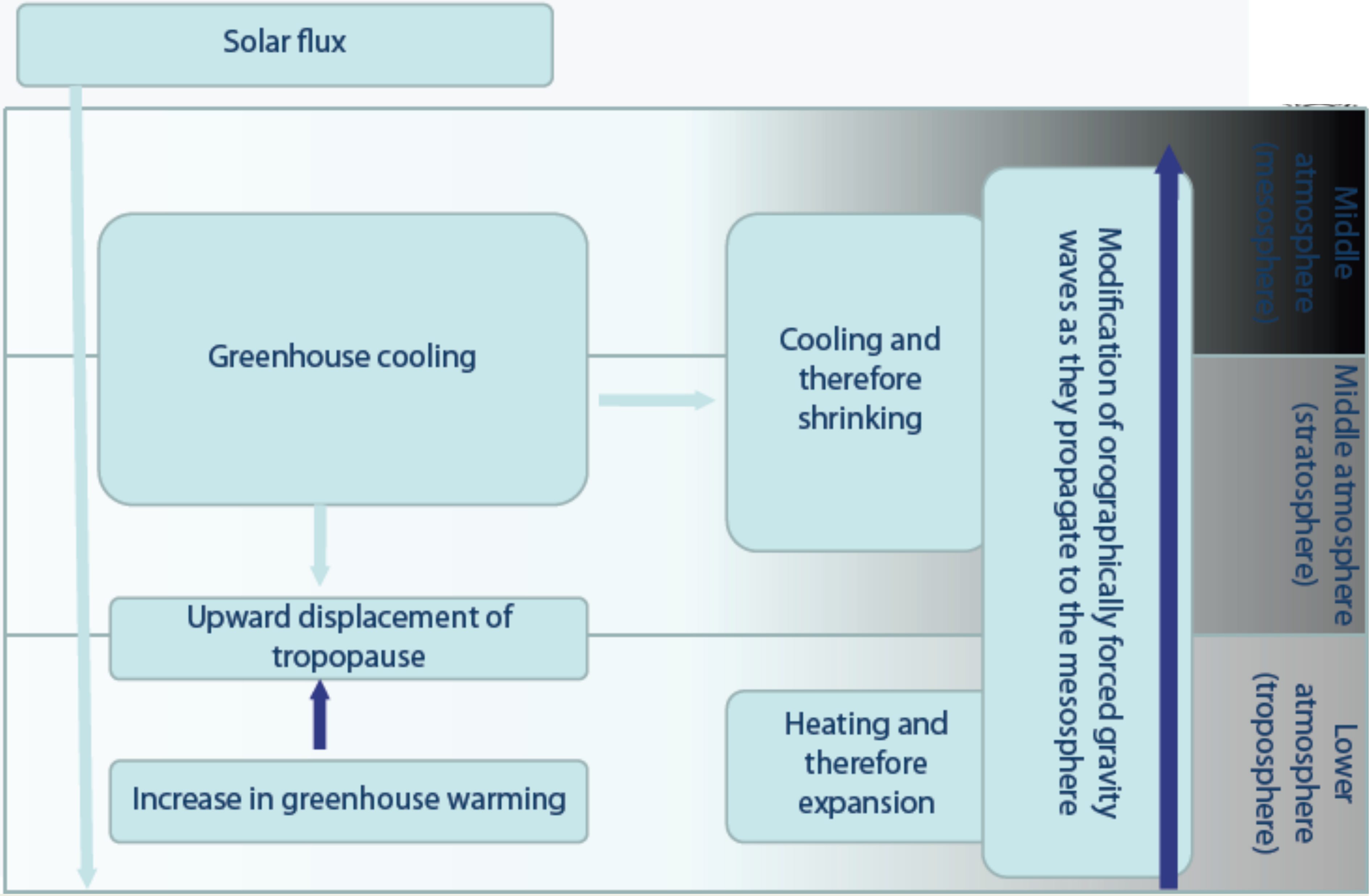
Rozanov et al., 2005 Seppälä et al., submitted



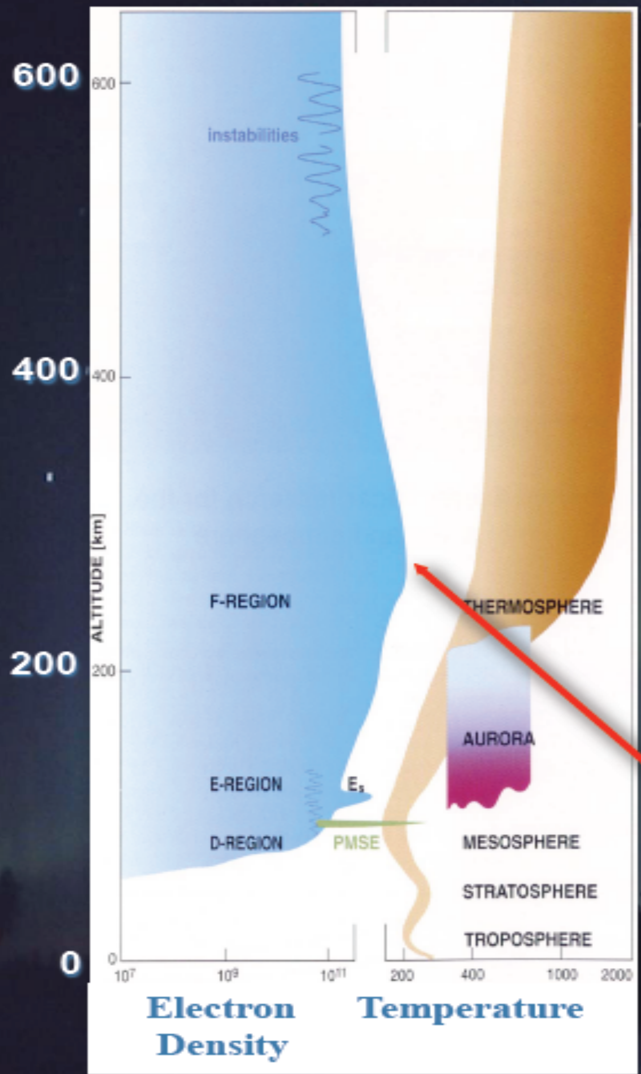
Downward control



Upward control



Atmospheric Coupling: Long-Term Trends



Greenhouse Cooling

Doubling of [CO_2] and [CH_4]

cools

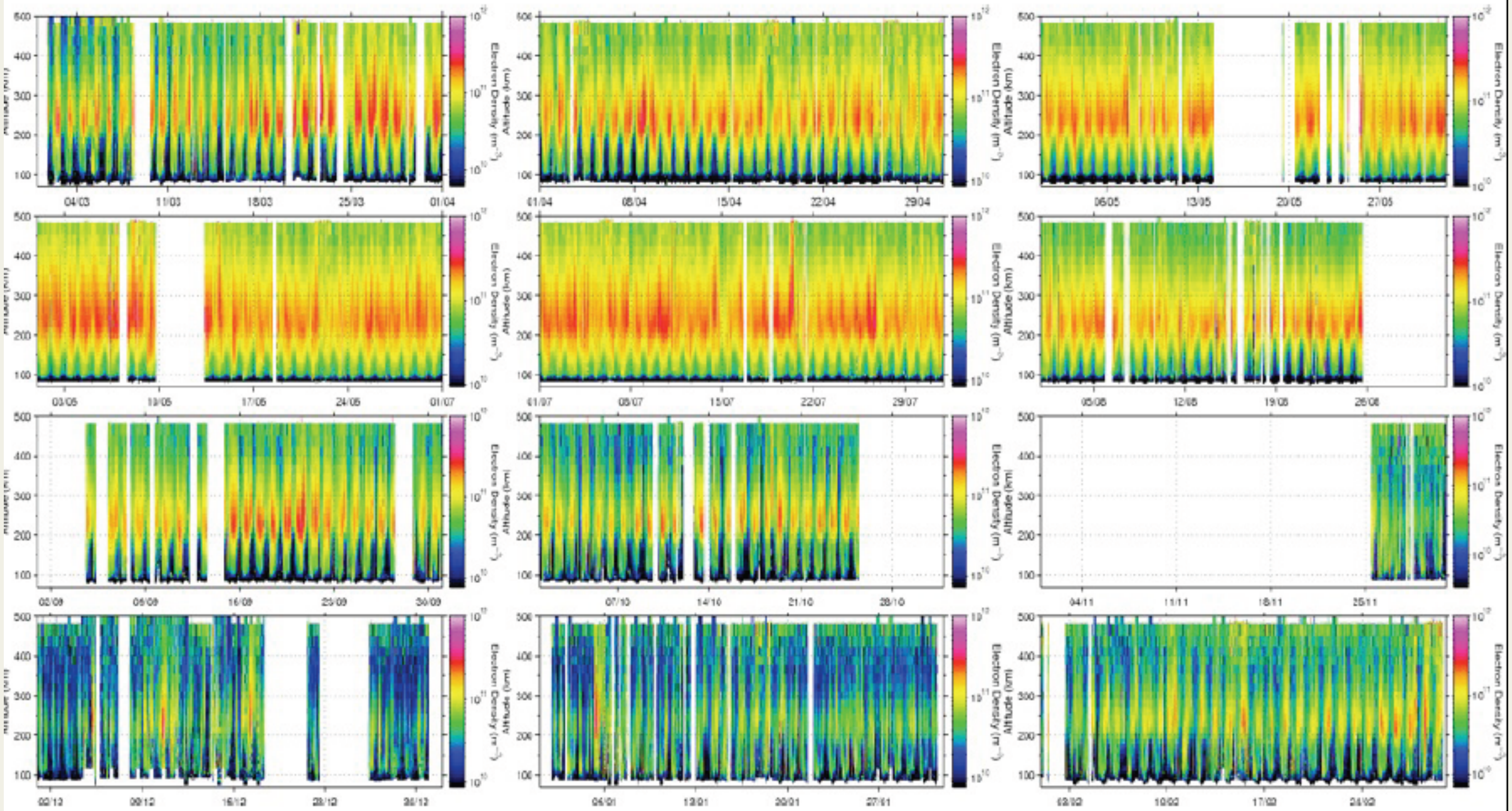
Mesosphere by **10 K** and Thermosphere by **50 K**.

Atmosphere shrinks.

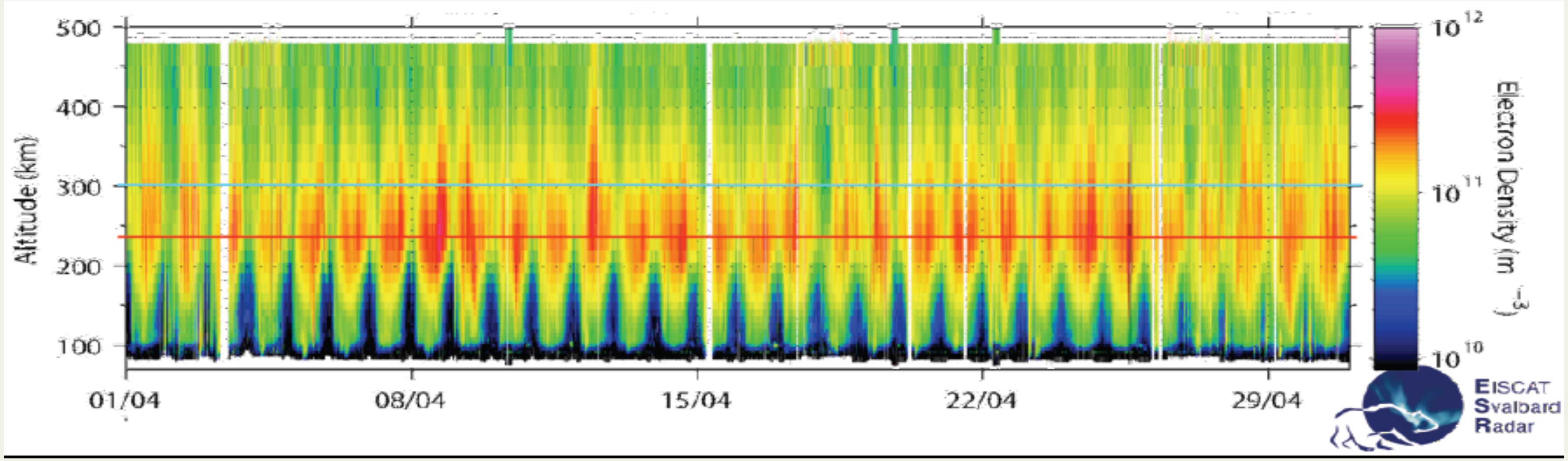
Layer of maximum electron density *lowers* by 15-20 km.

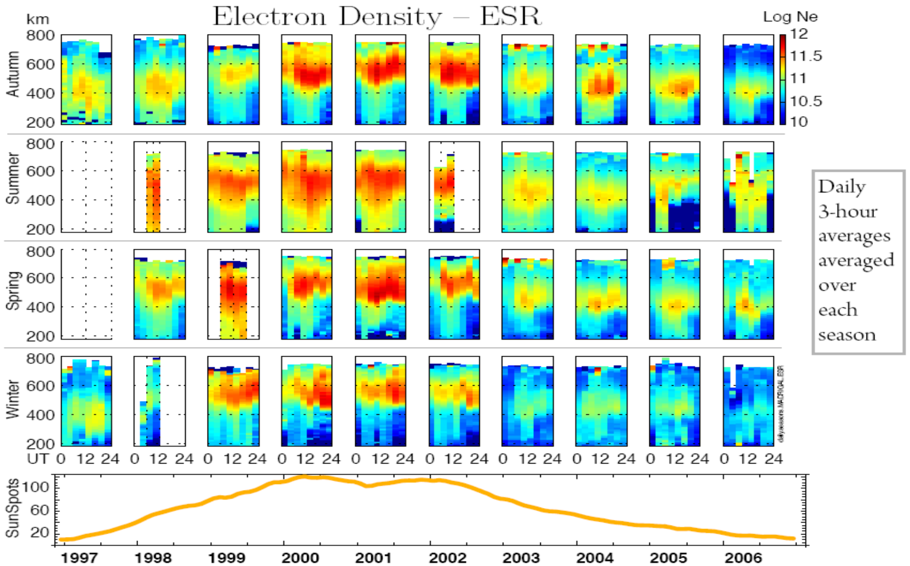
Continuous, long-period data

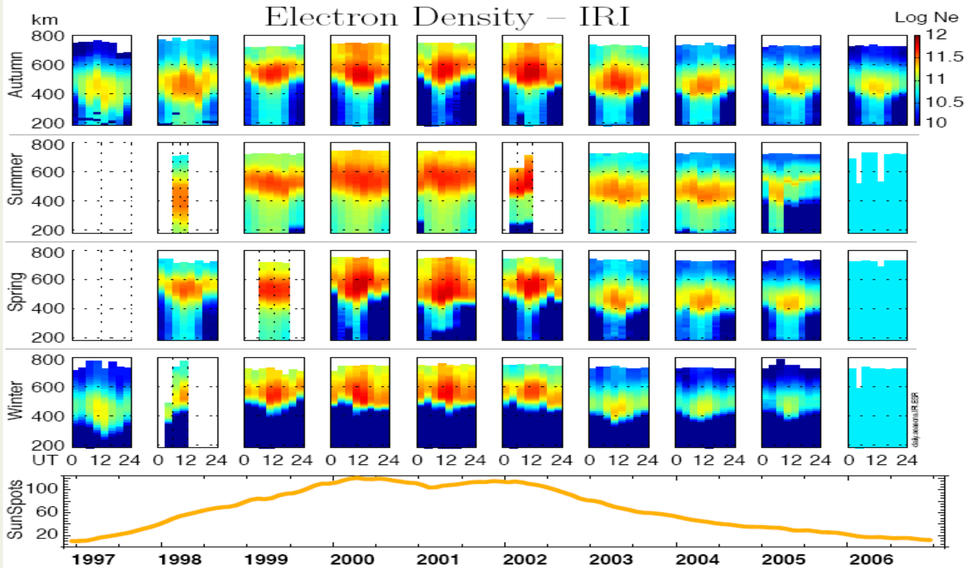
EISCAT Svalbard Radar data: Spring, Summer, Autumn, Winter



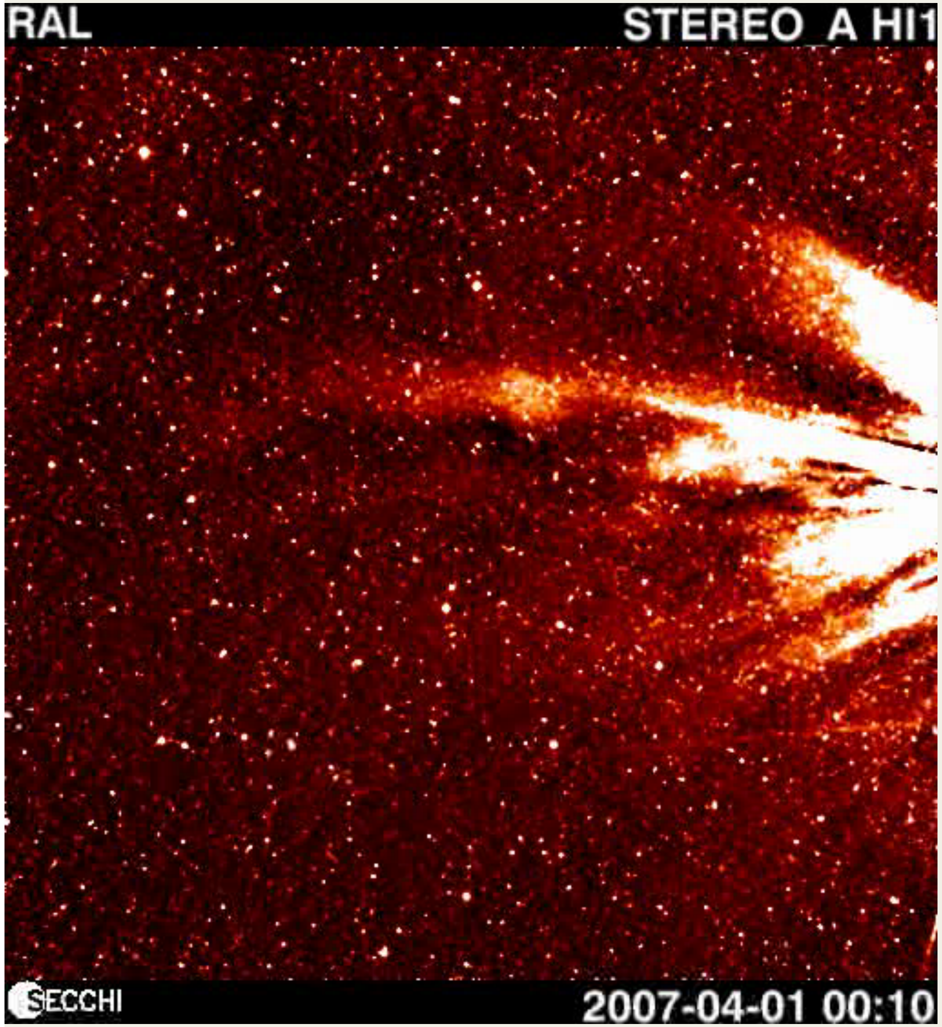
Large-scale processes: Predictability

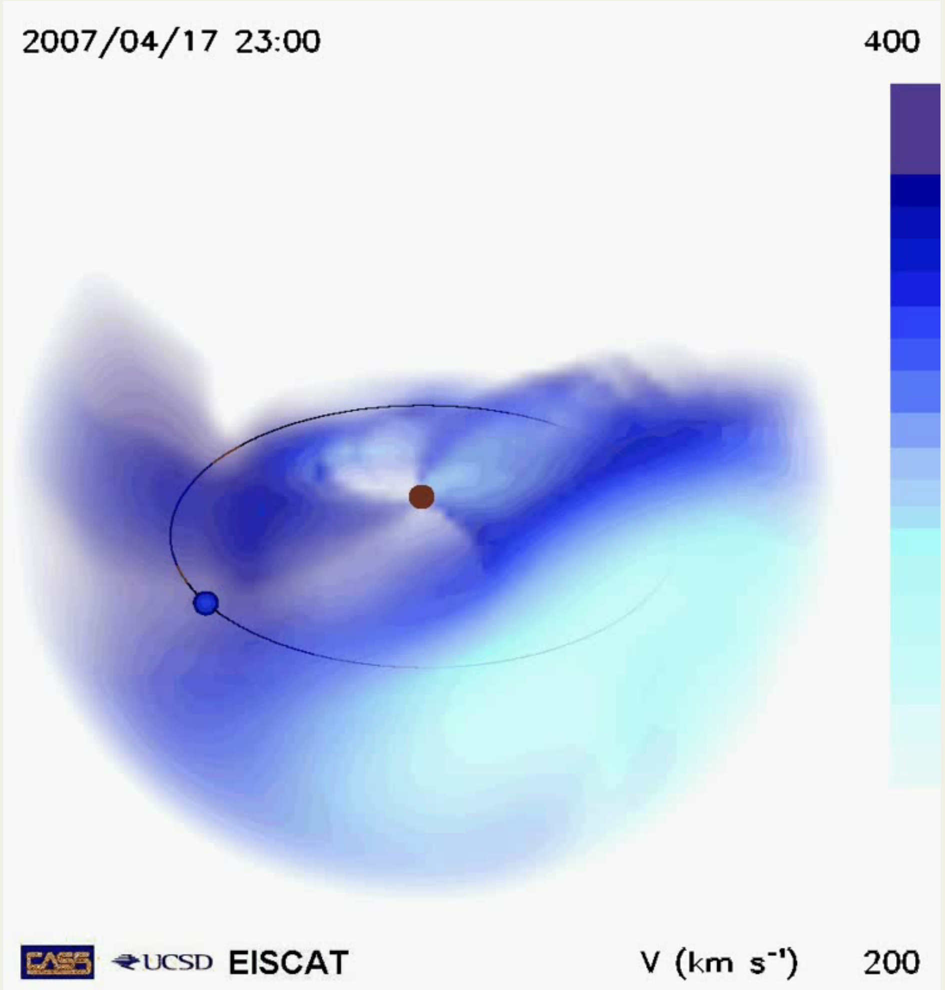




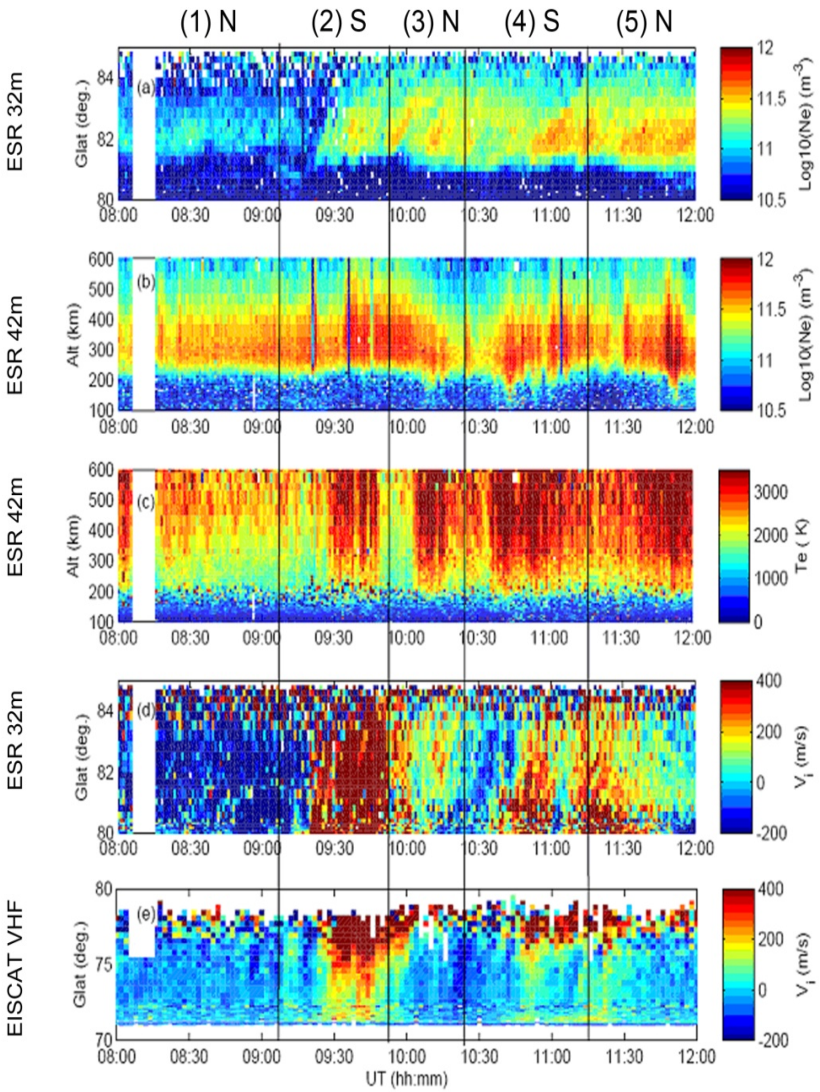


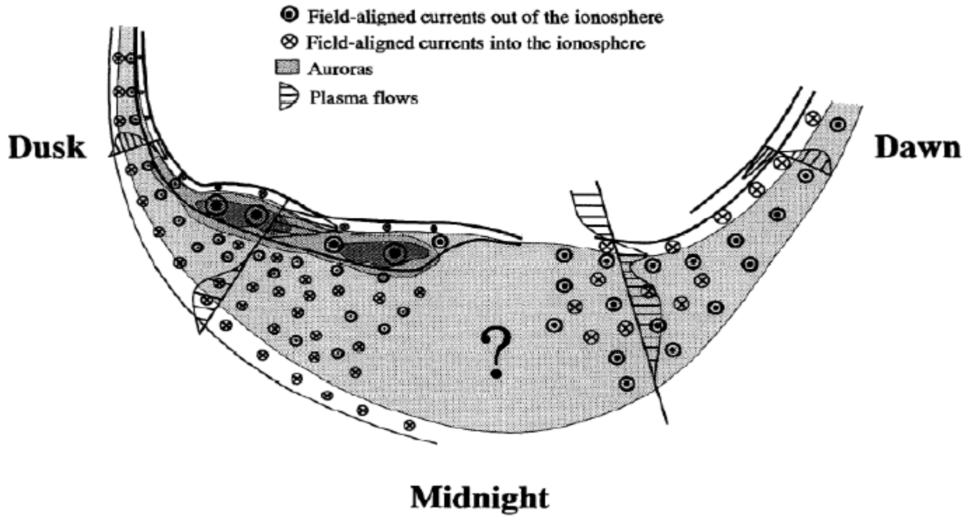
Large-scale processes: From Sun to Earth

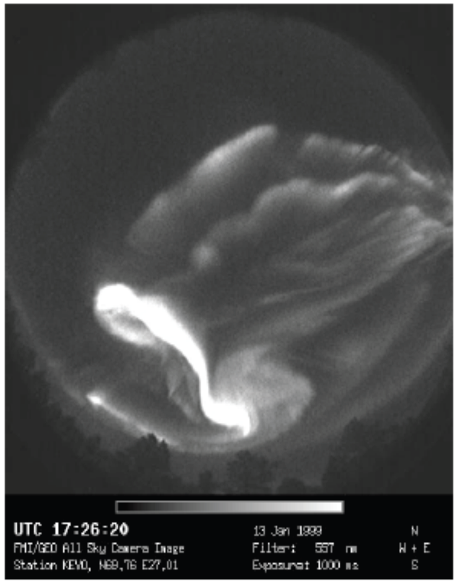


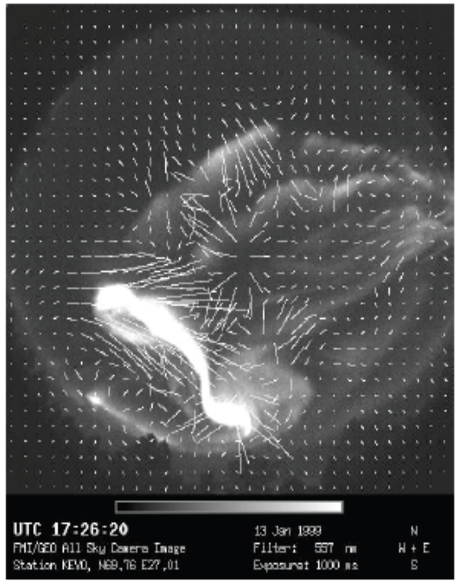


Large-scale processes: Magnetosphere imaging

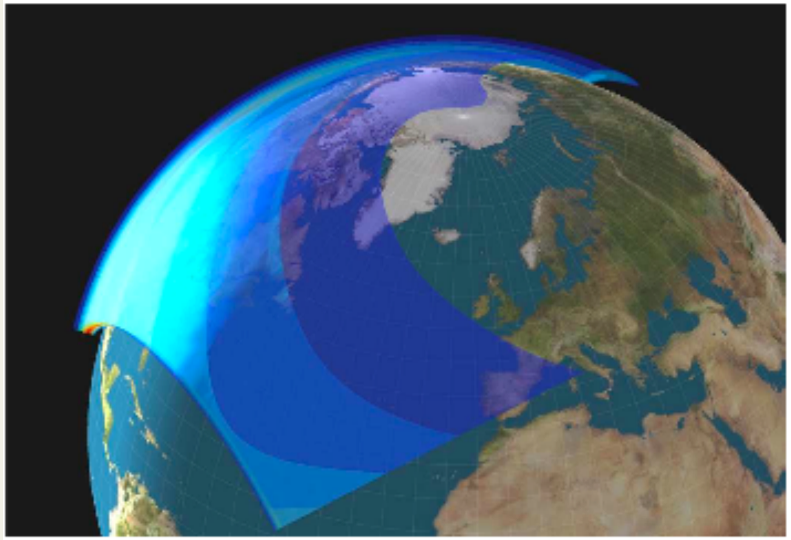
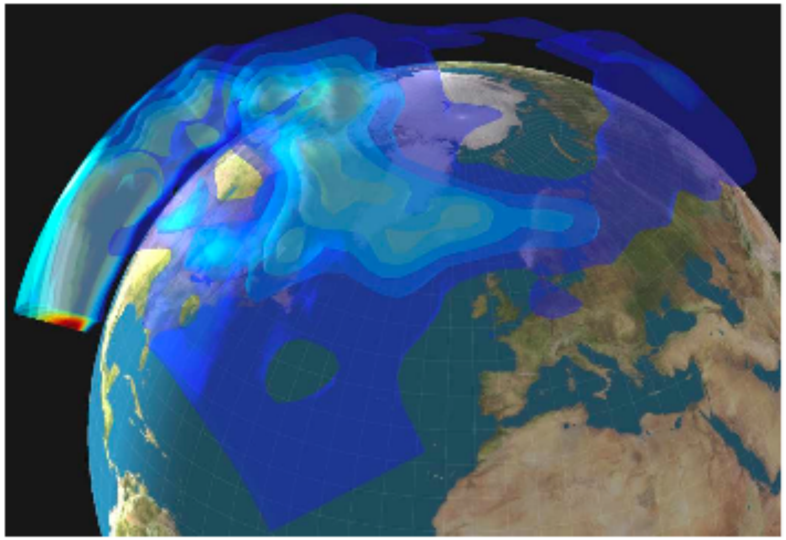
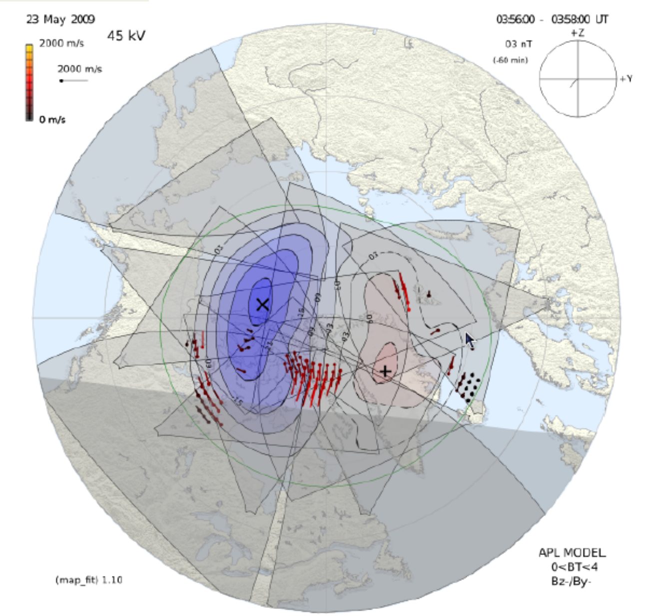


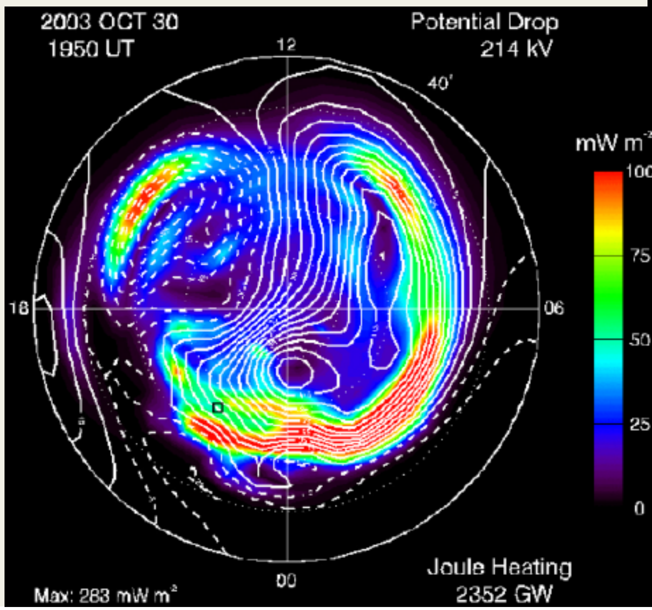


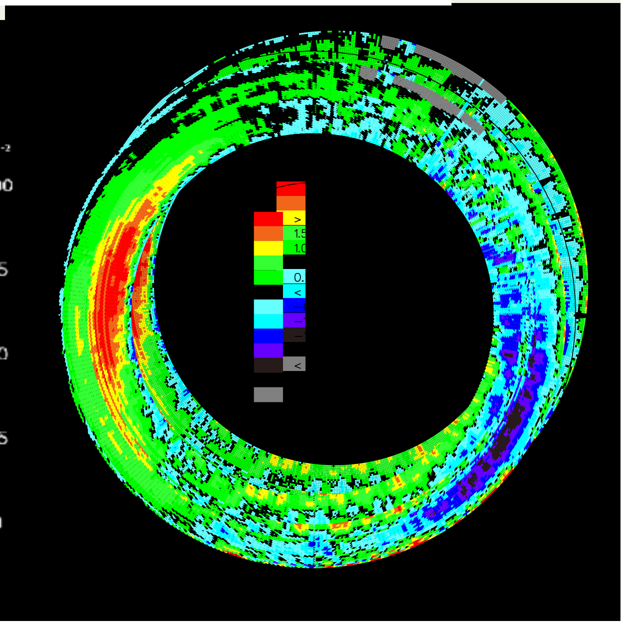




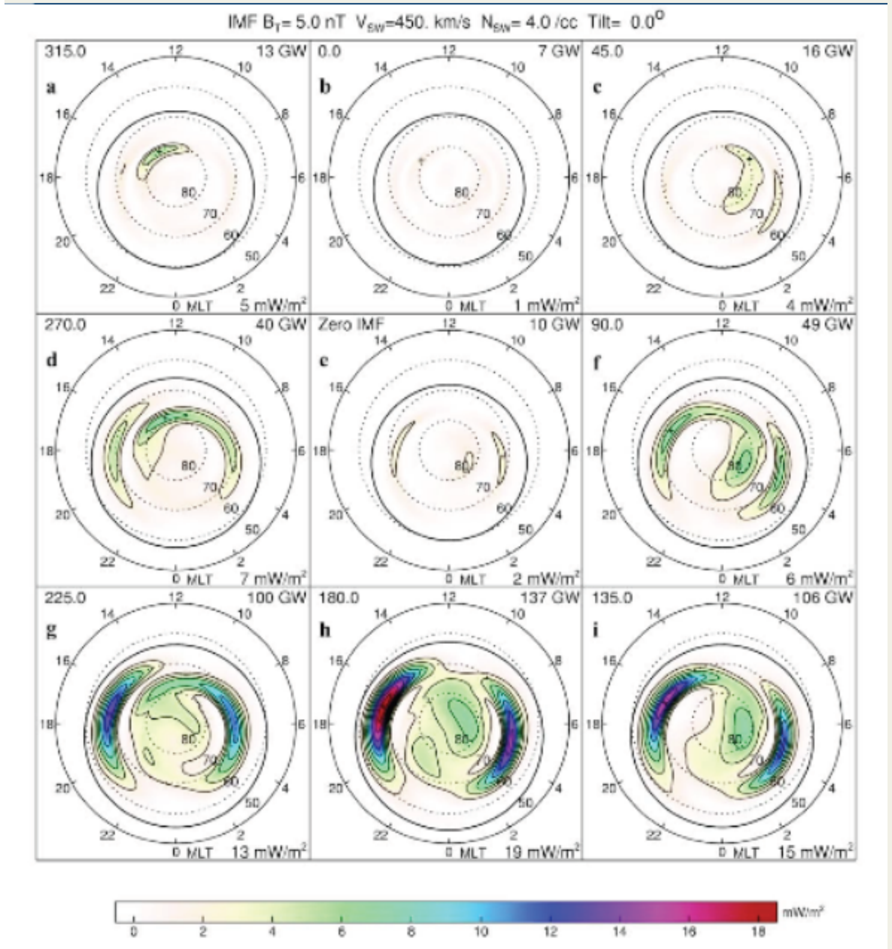
Large-scale processes: Energy deposition

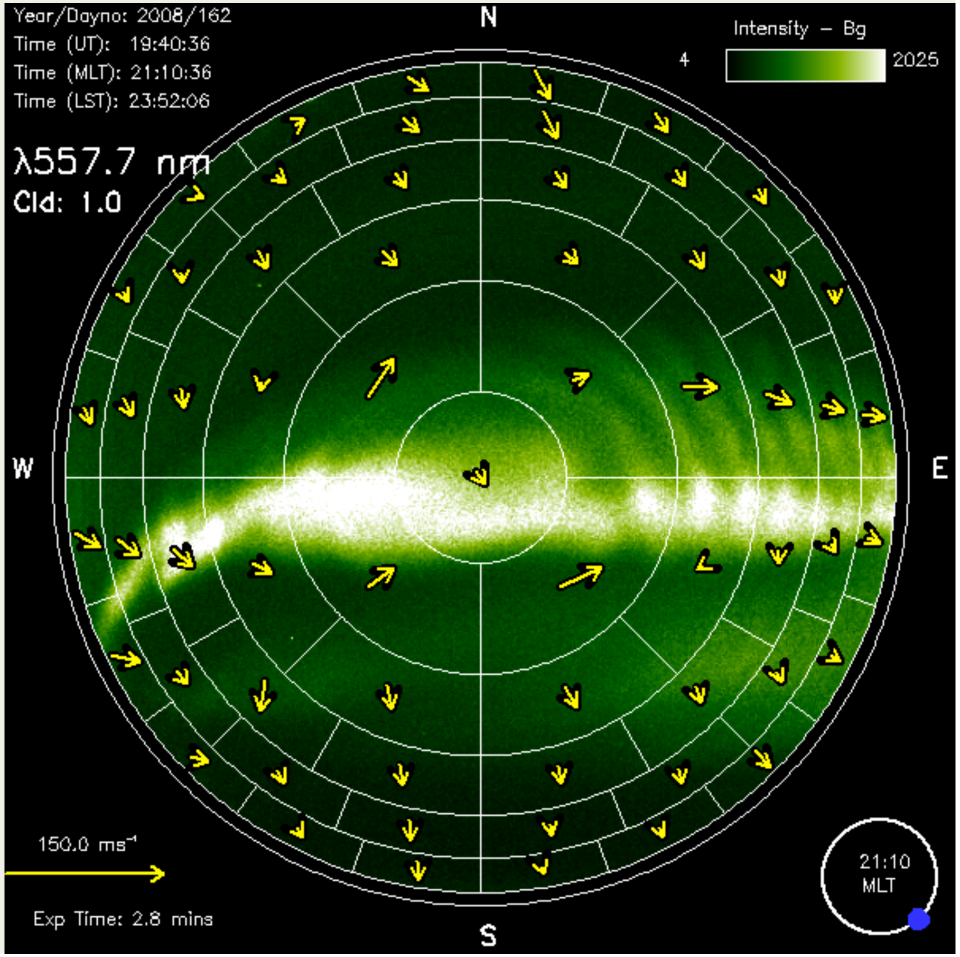






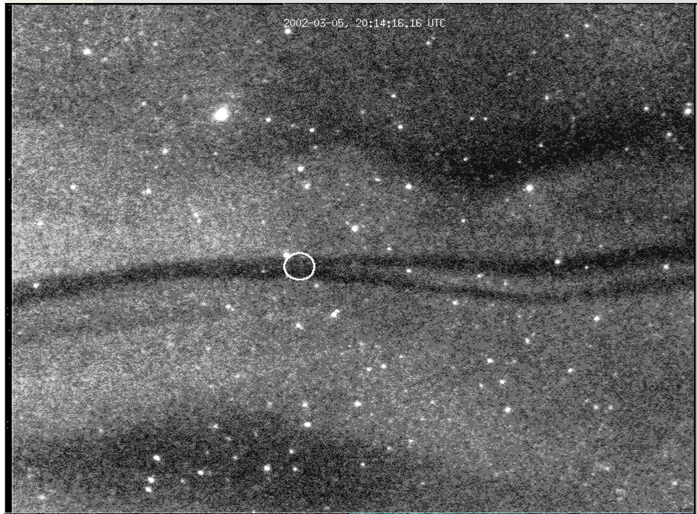


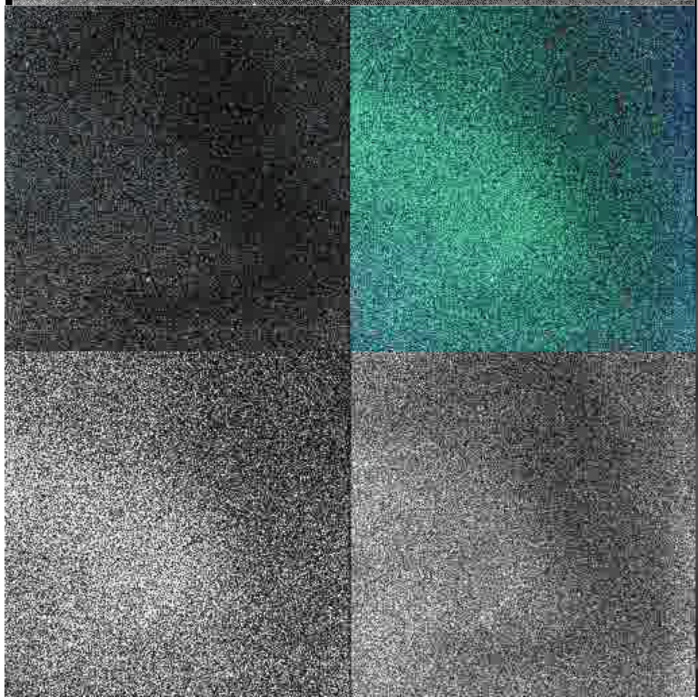
Small-scale processes: Effect on larger scales

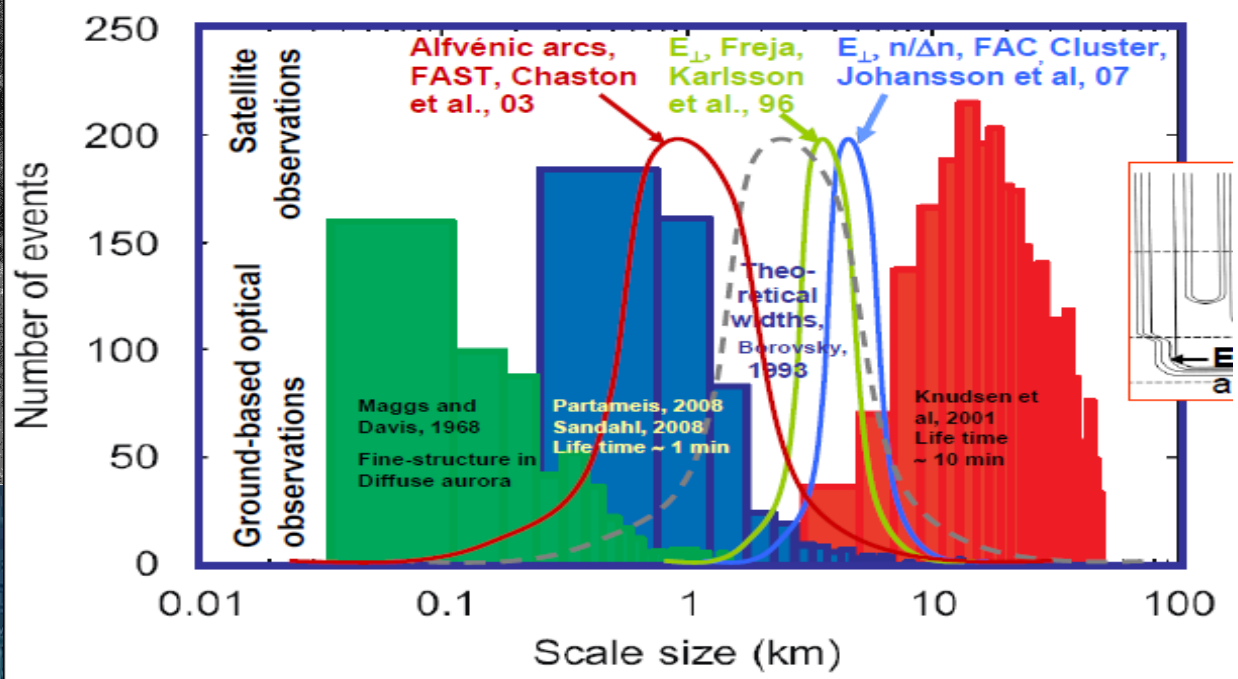


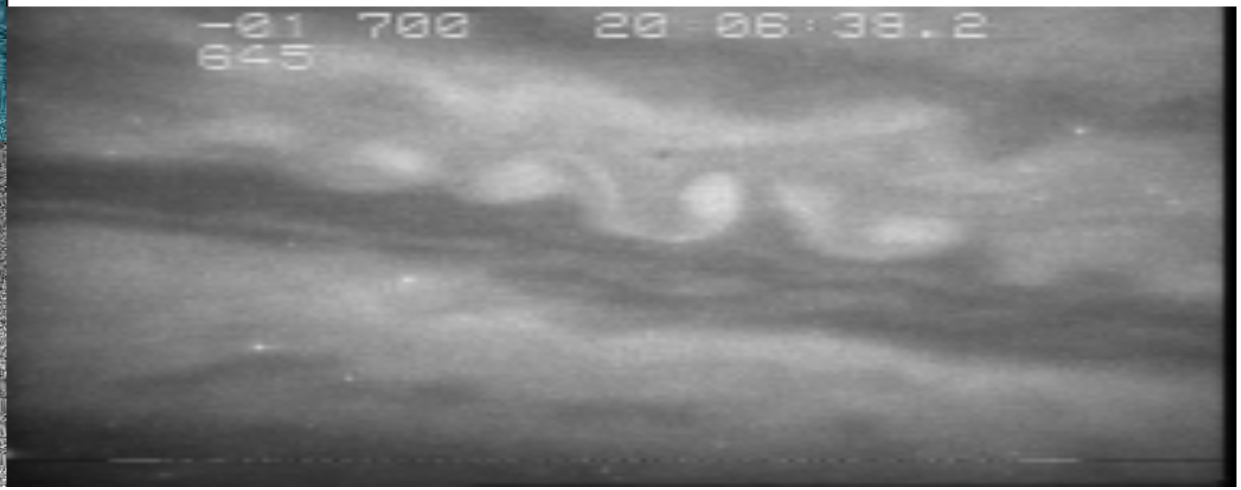


Small-scale structure: Auroral physics

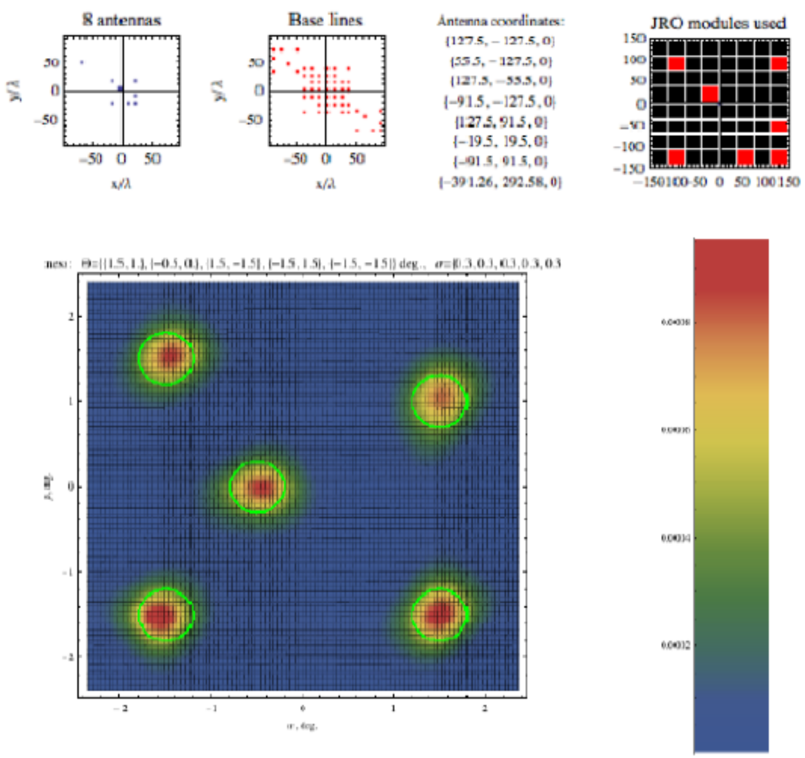


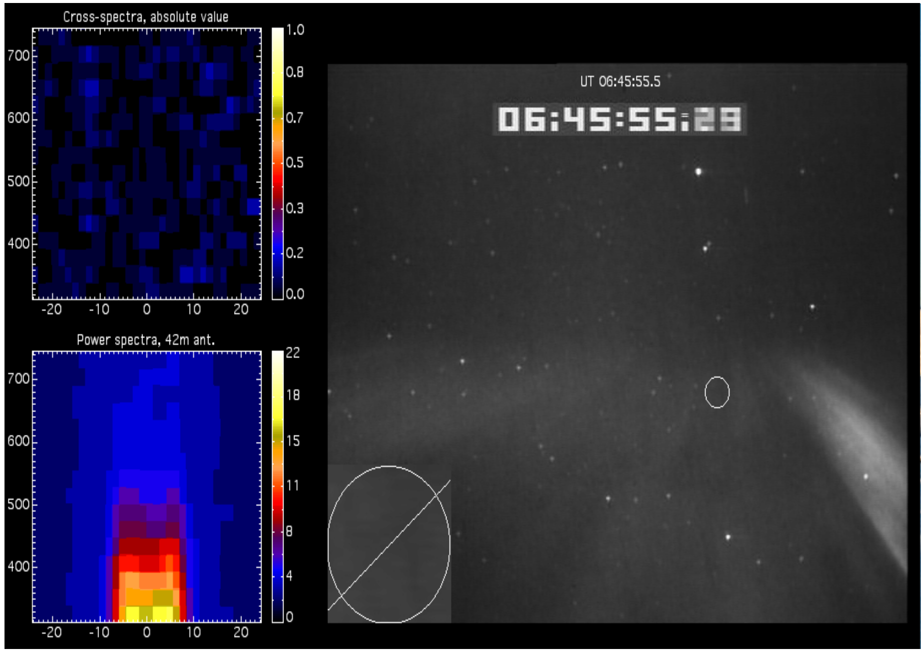


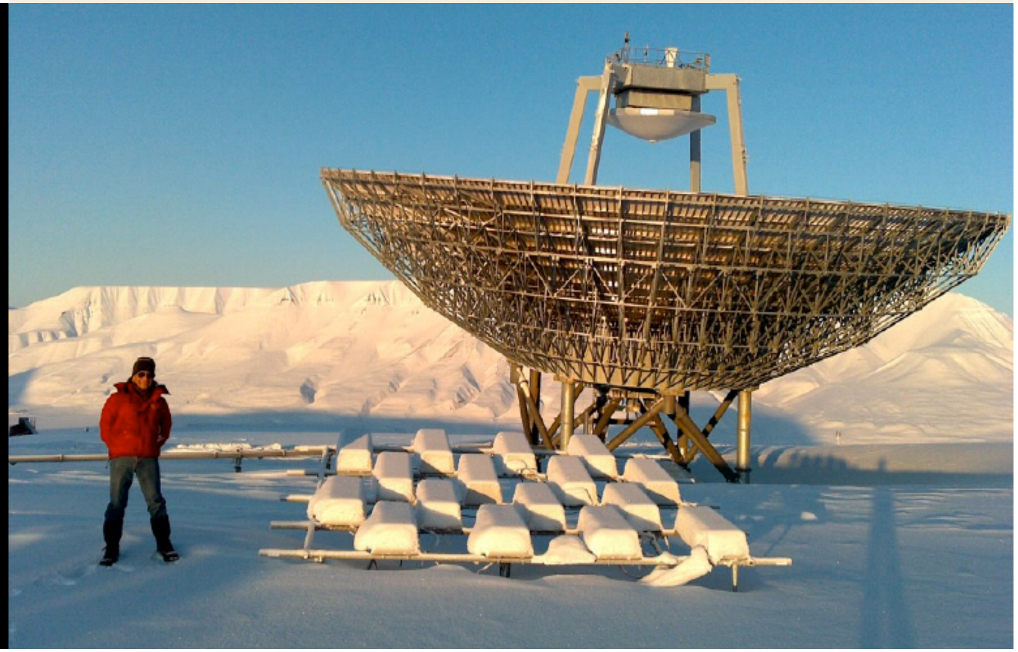




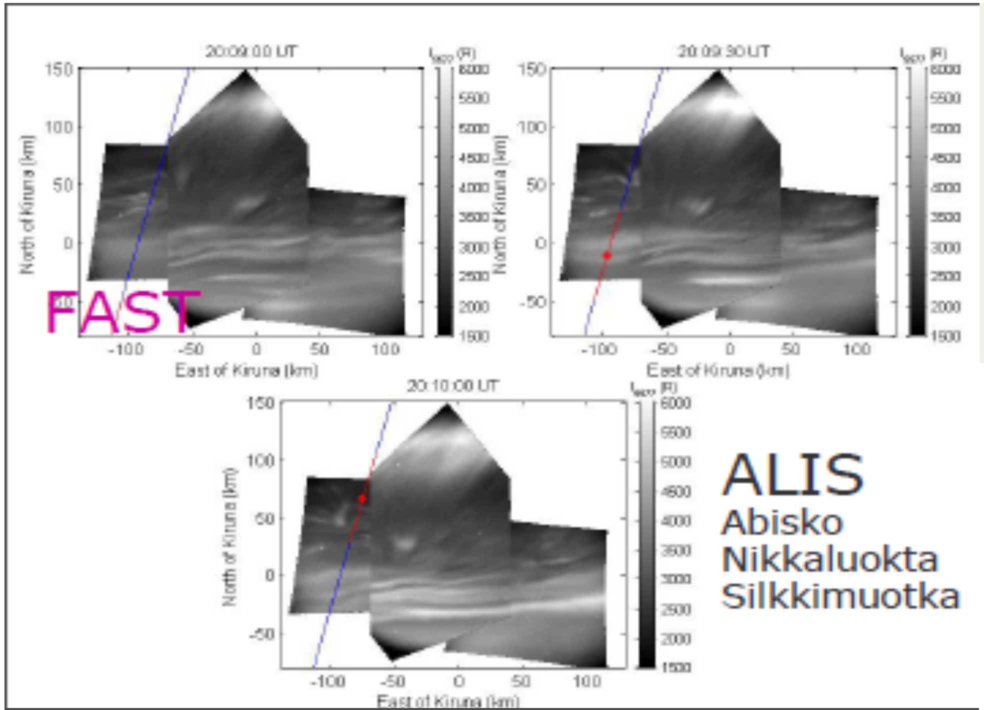
Small-scale structure: Current EISCAT studies

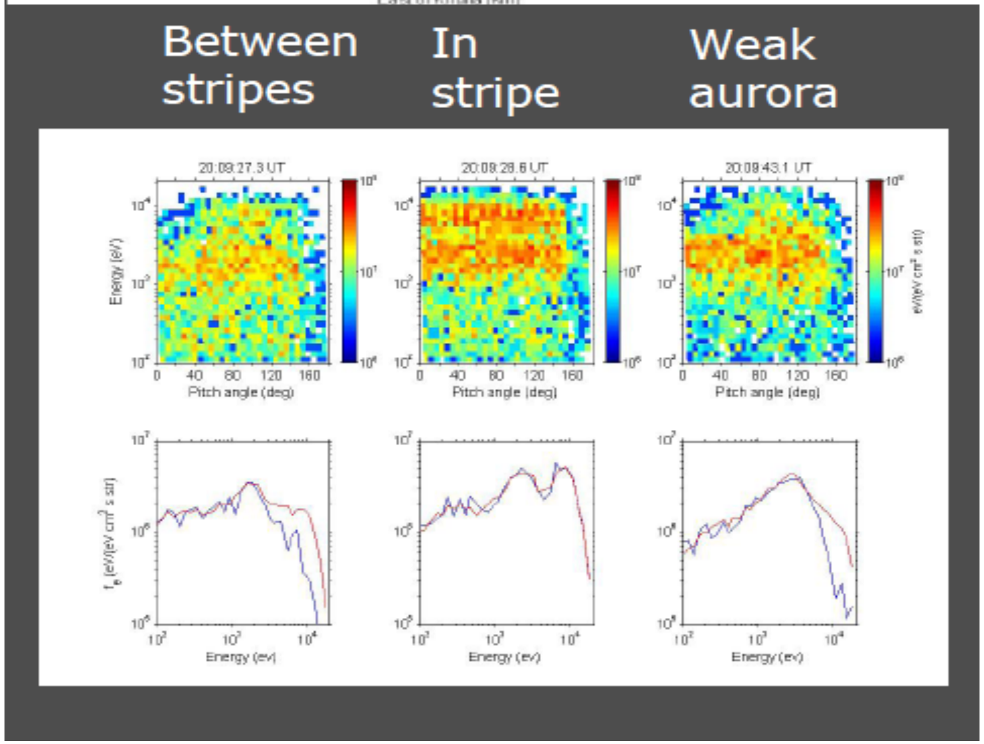


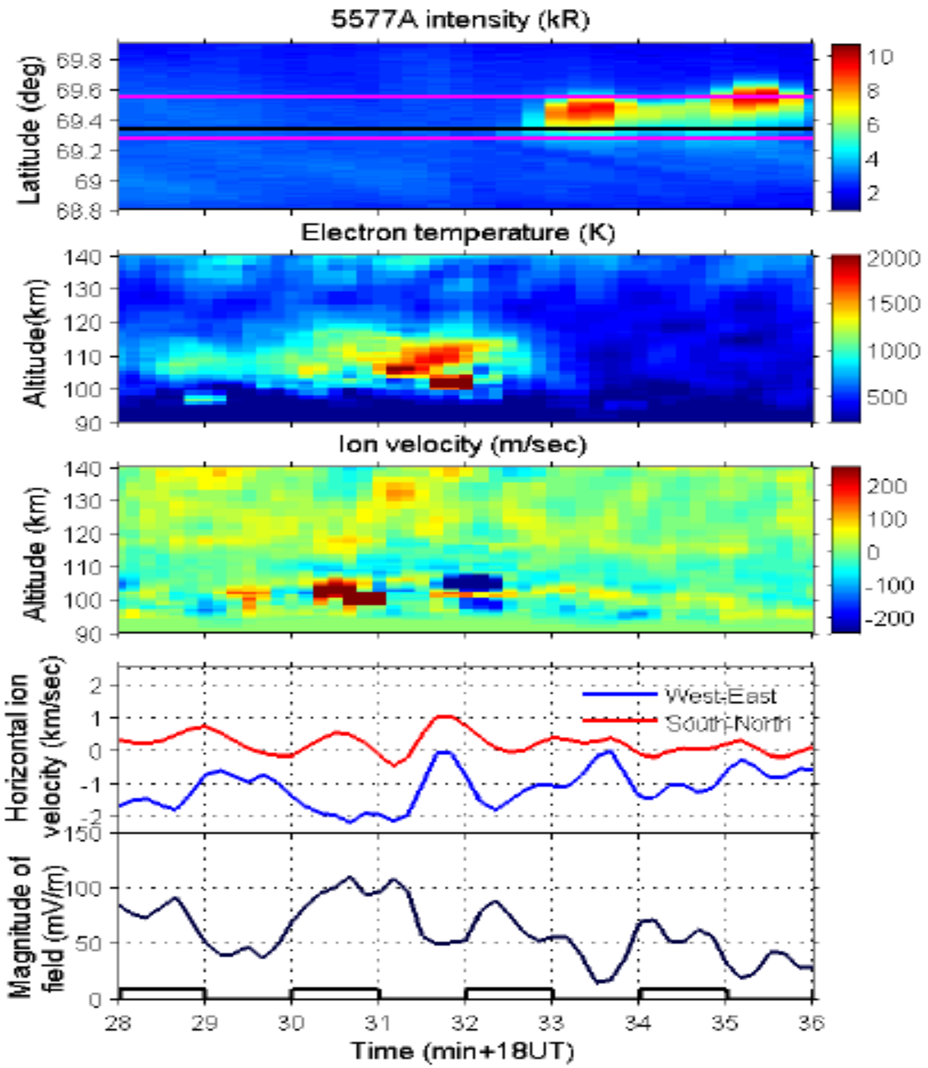




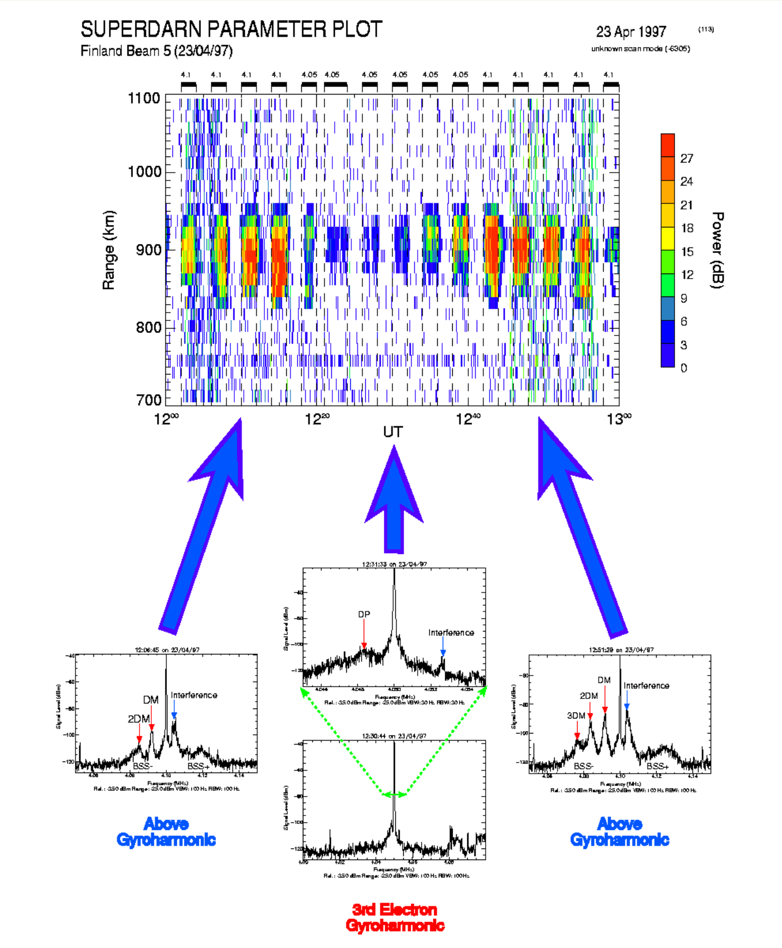
Small-scale structure: Wave Coupling

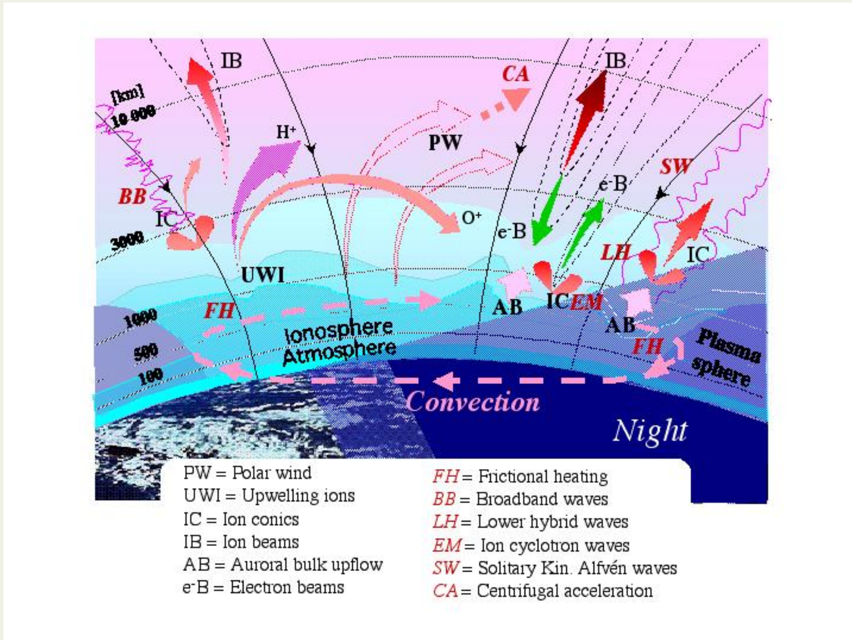




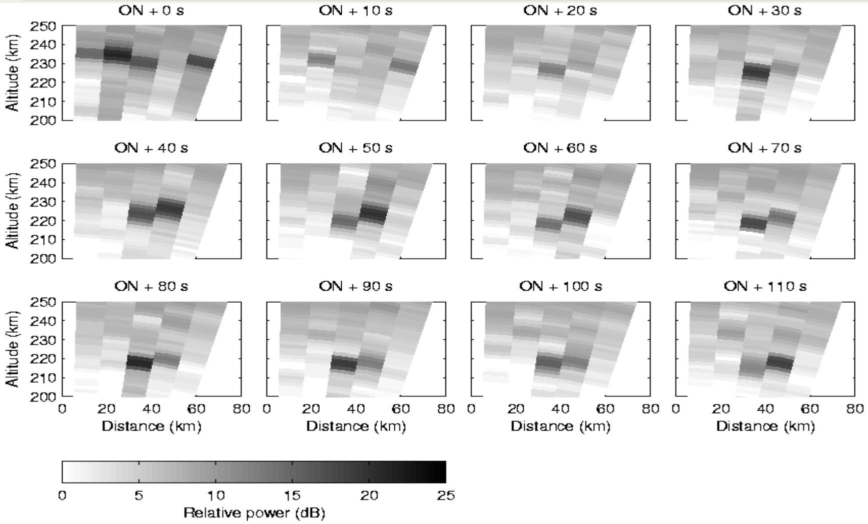


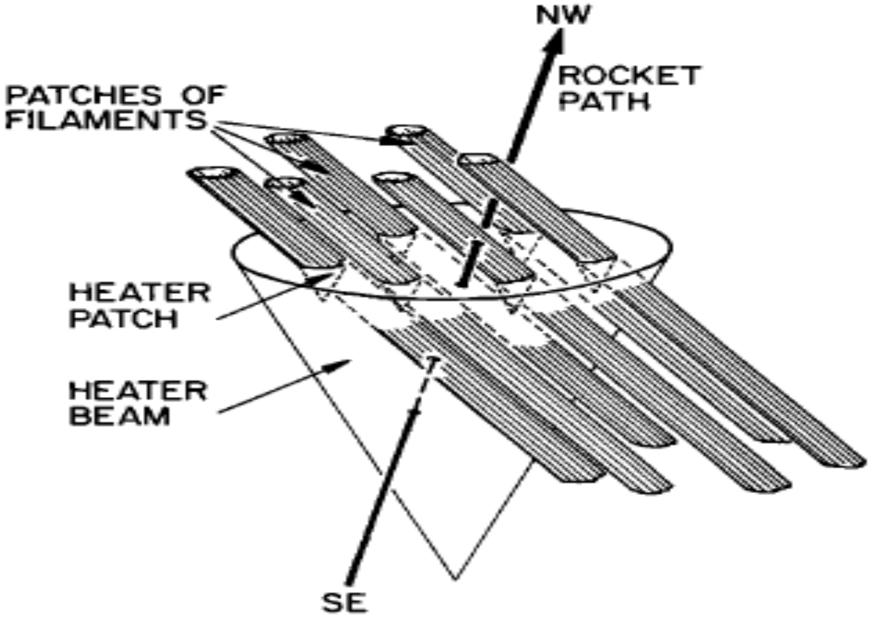
Plasma Physics:
Wave-wave and wave-particle interactions





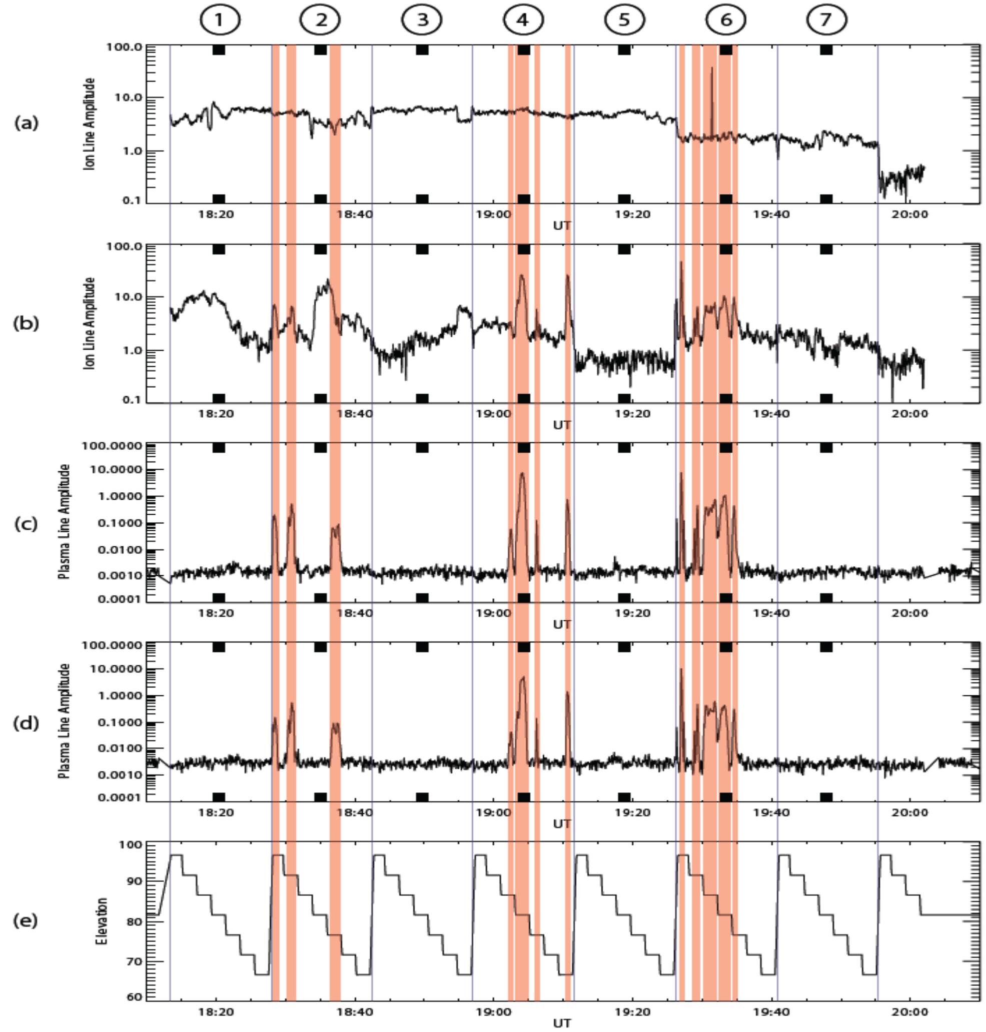
Plasma Physics: Waves and turbulence



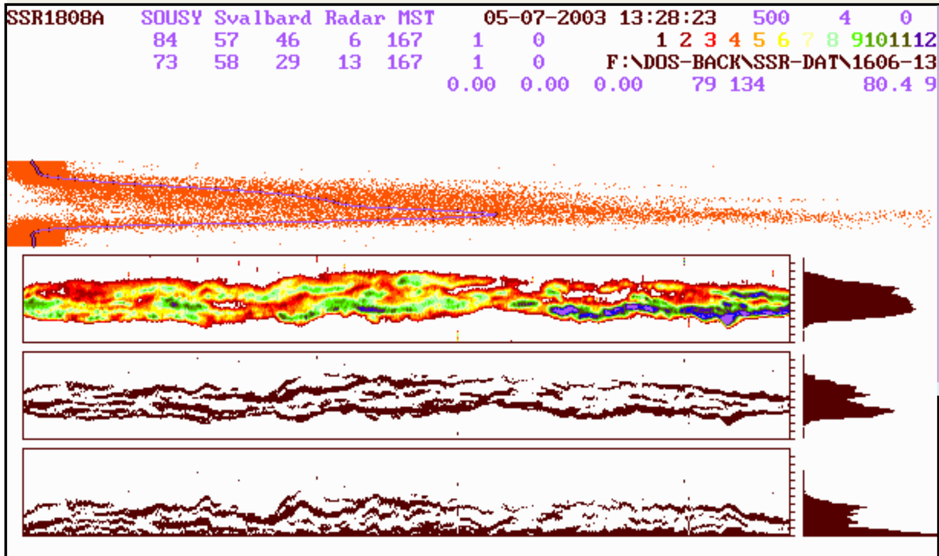


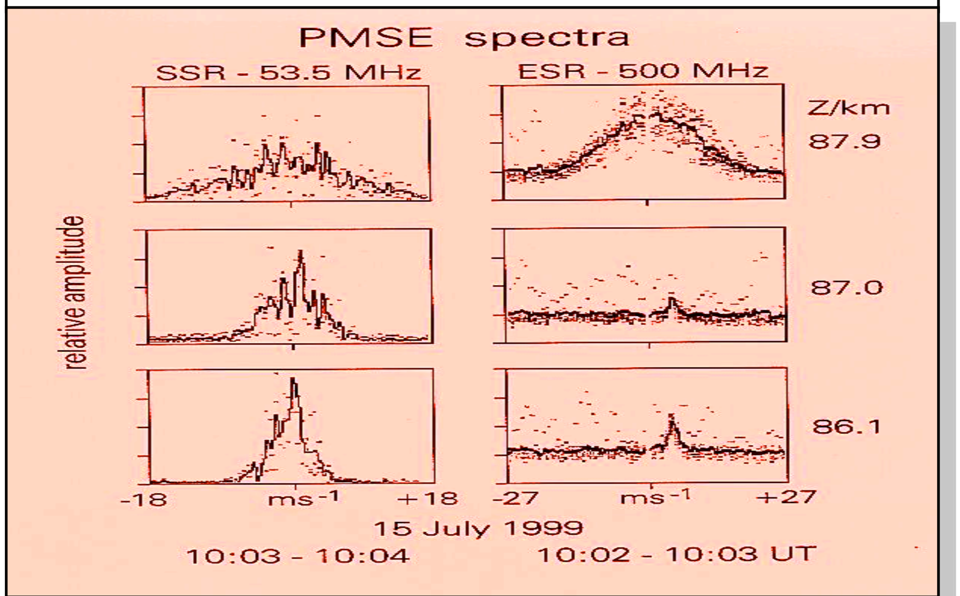
ESR BACKSCATTER DATA

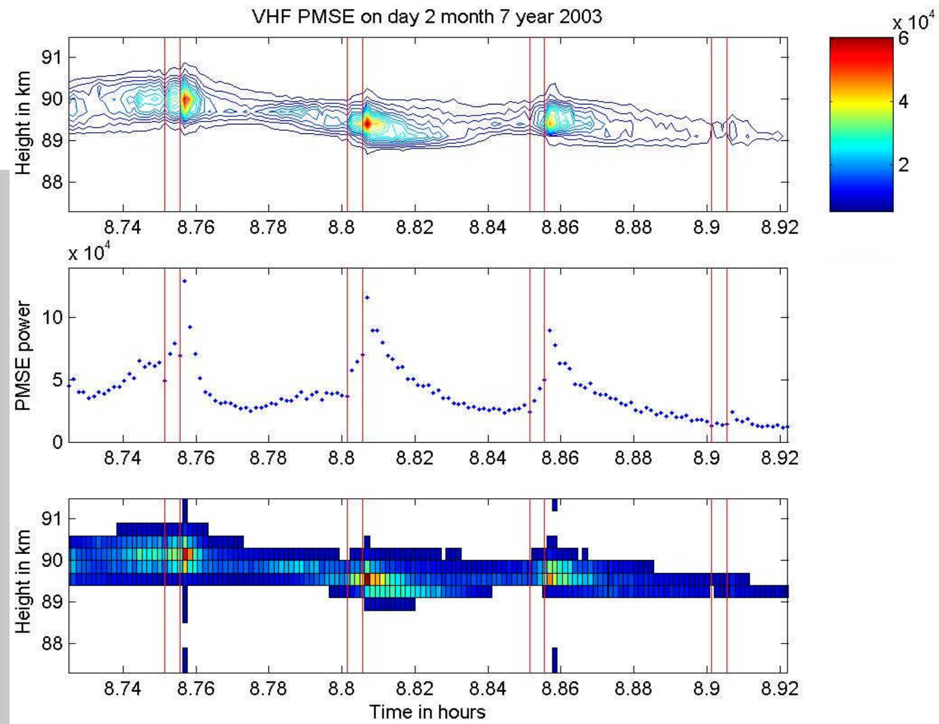
F-CIL, E-CIL, UPL and DPL on 07/12/2005



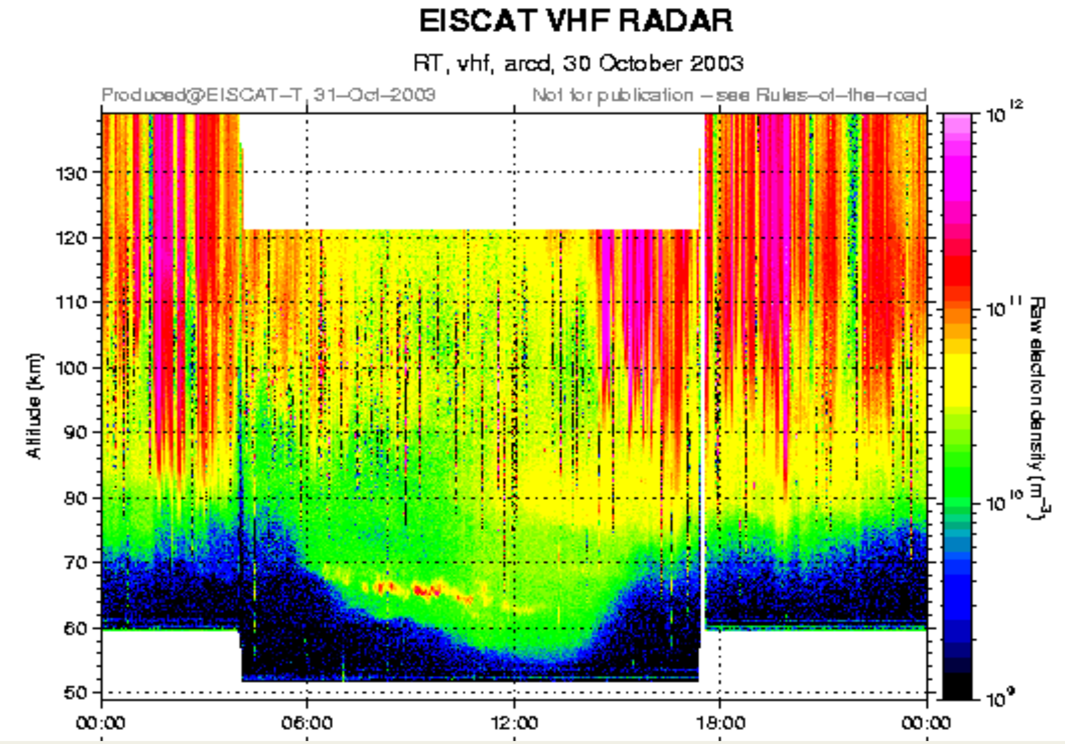
Plasma Physics: Dusty Plasmas

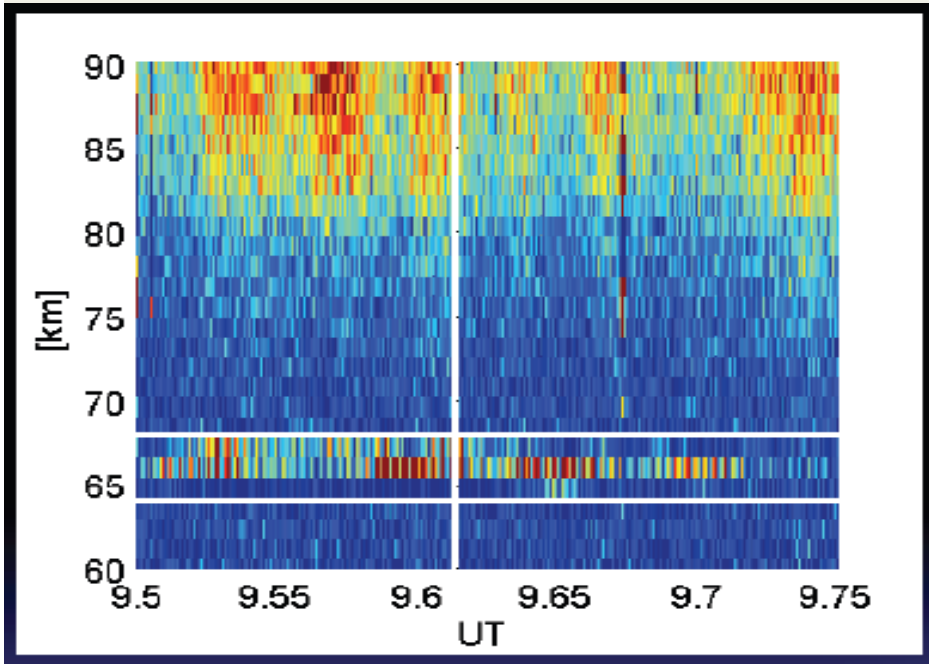


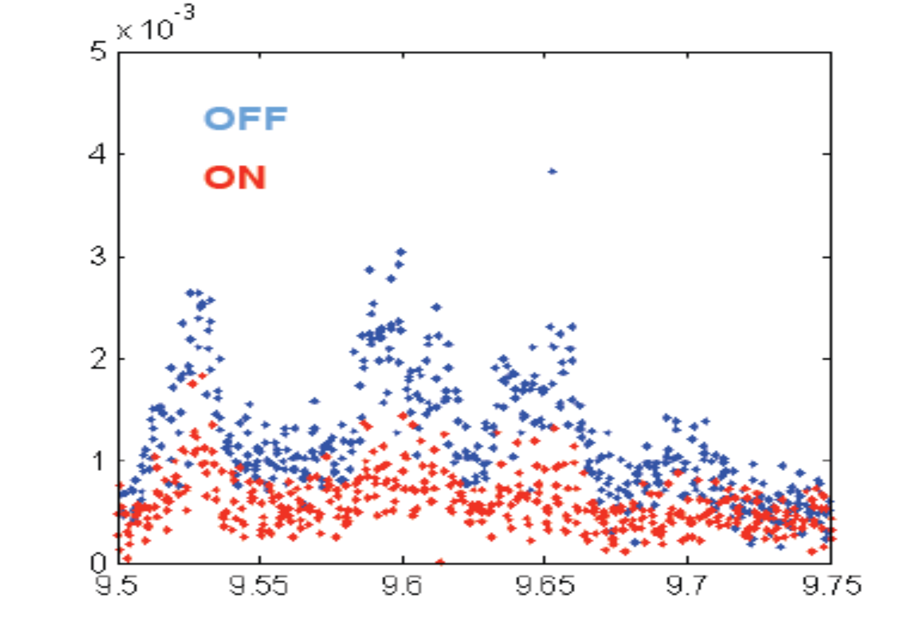




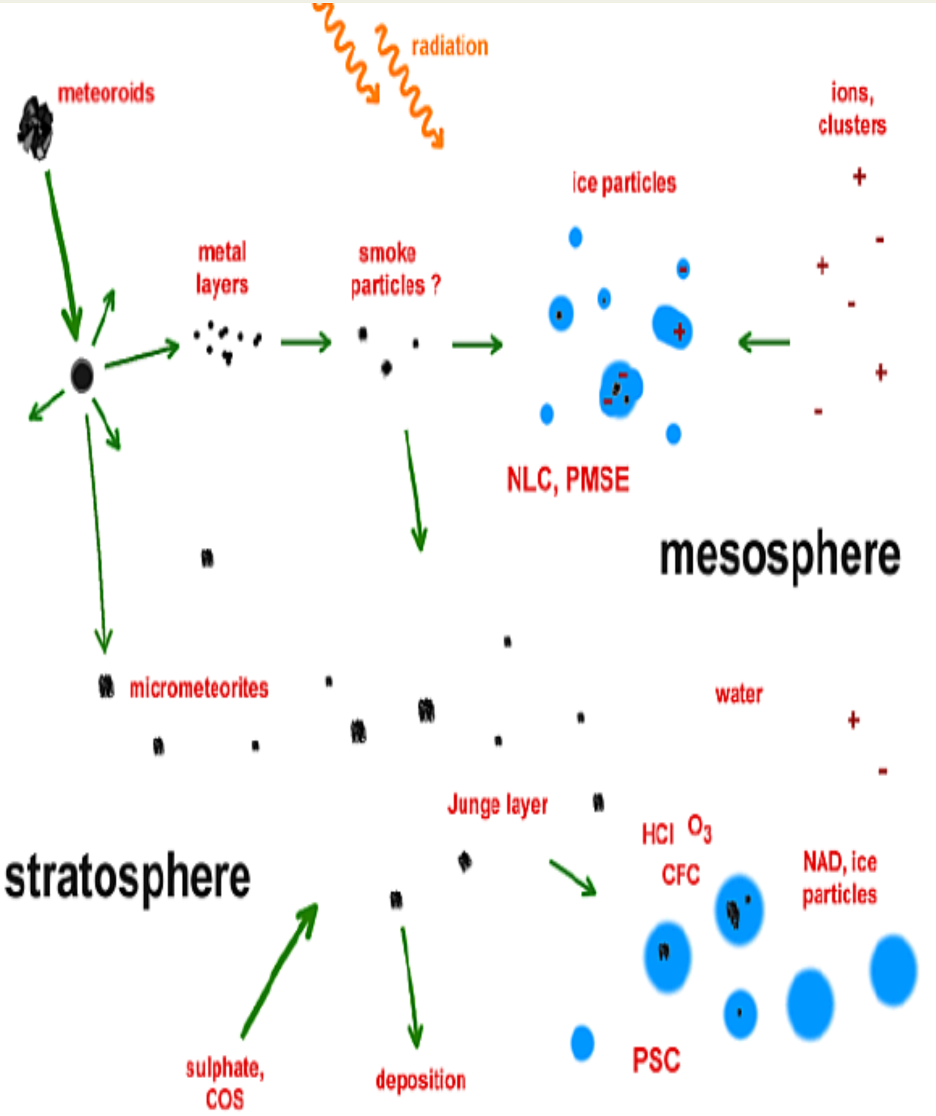
Polar Mesospheric Winter Echoes

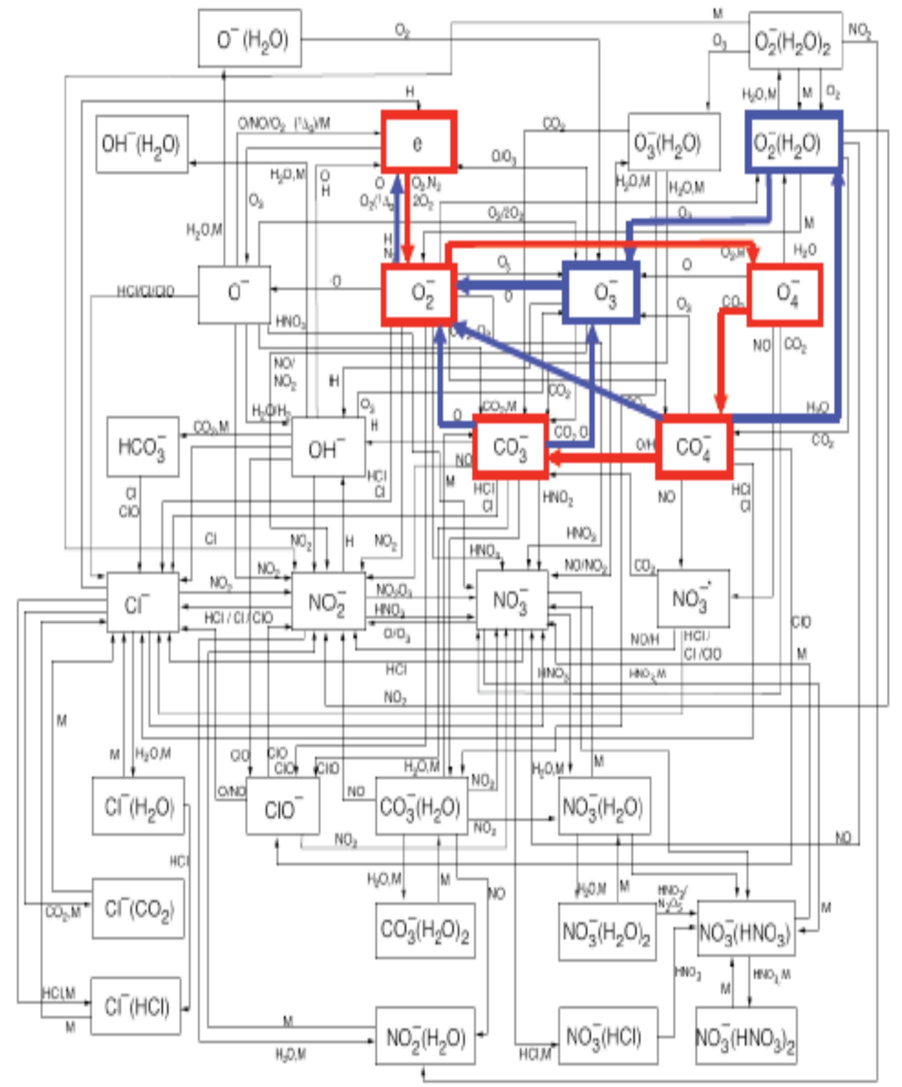




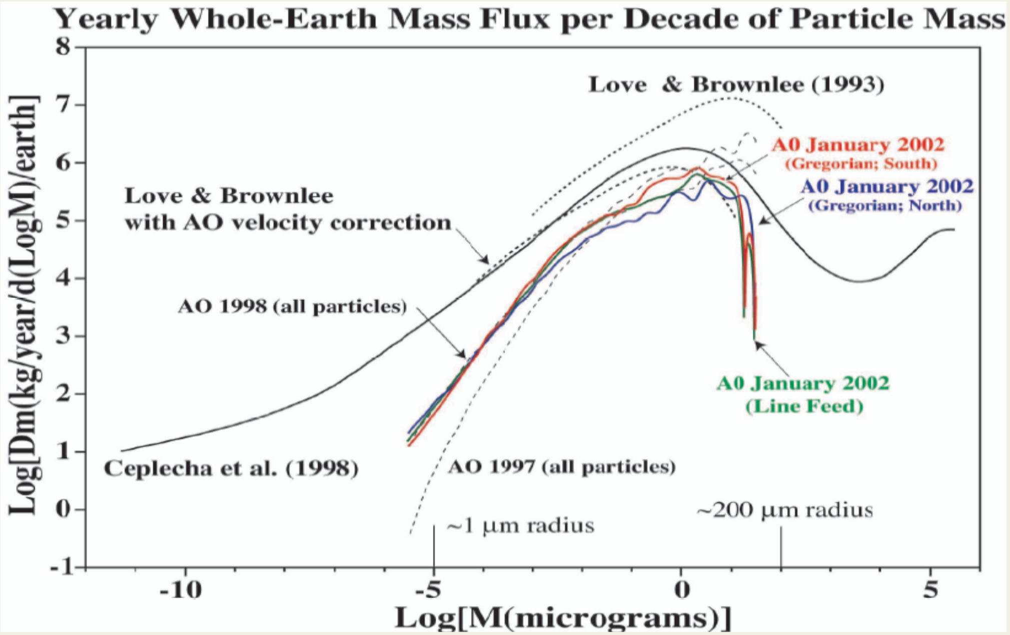


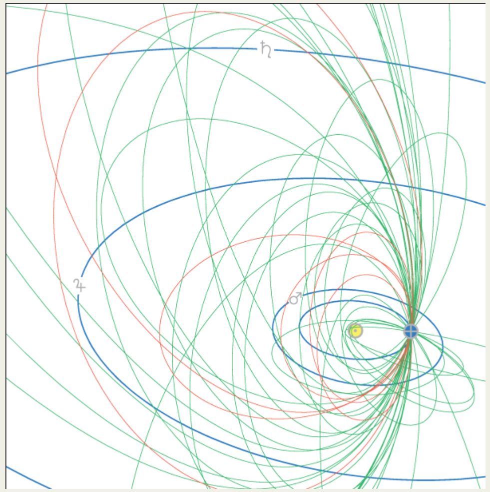
Meteors and Chemistry

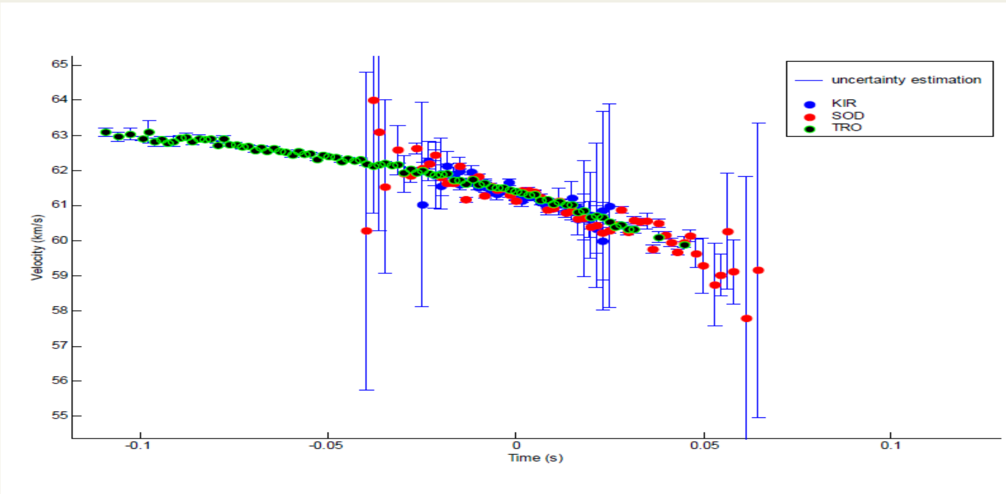


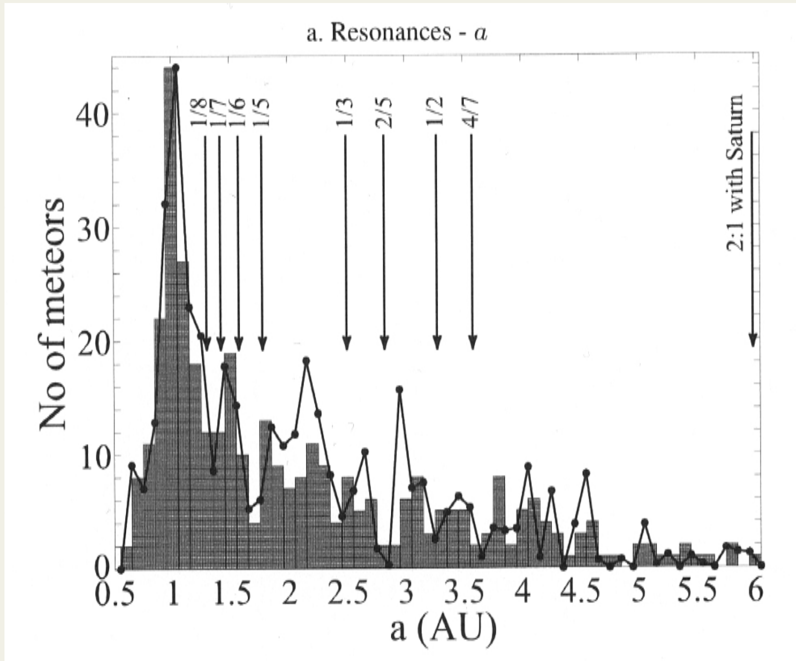


Geospace Environment: Meteors

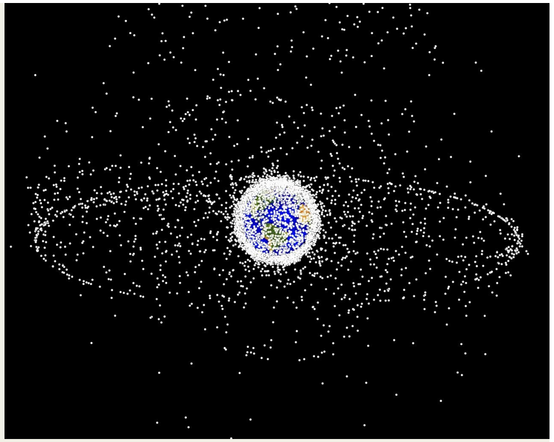


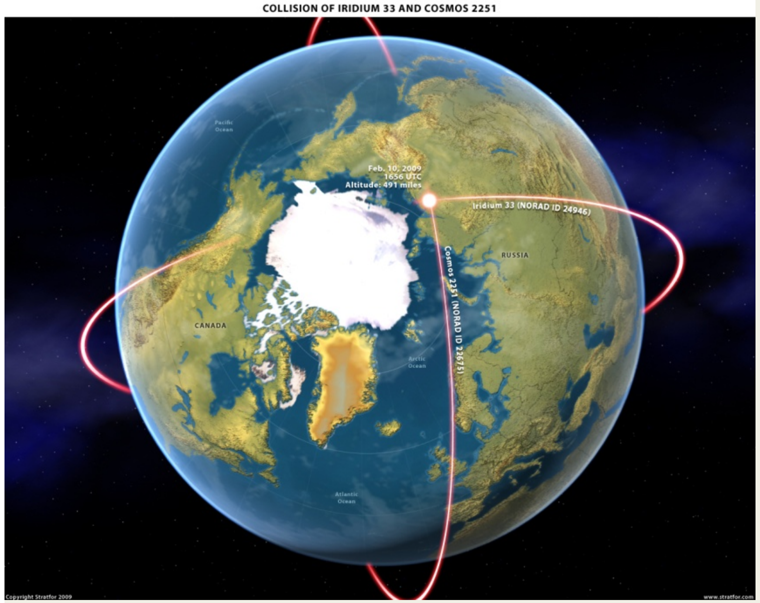


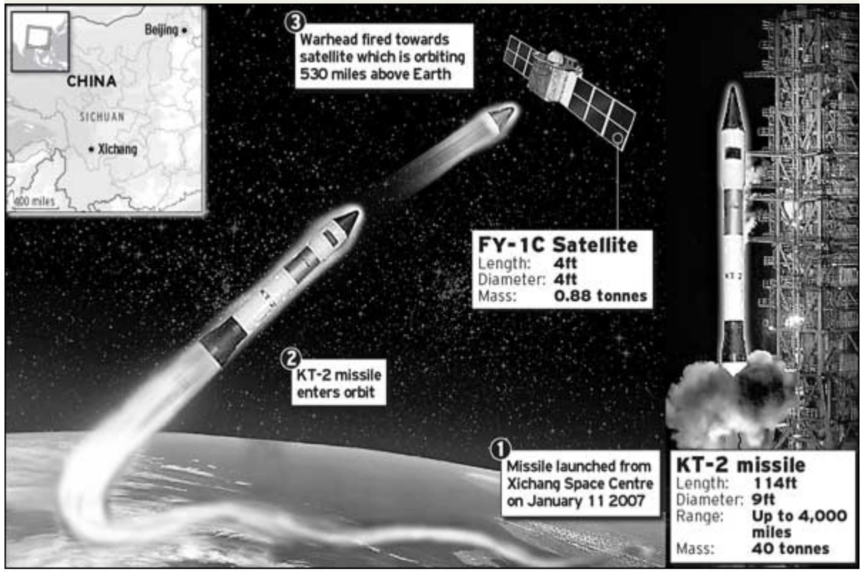


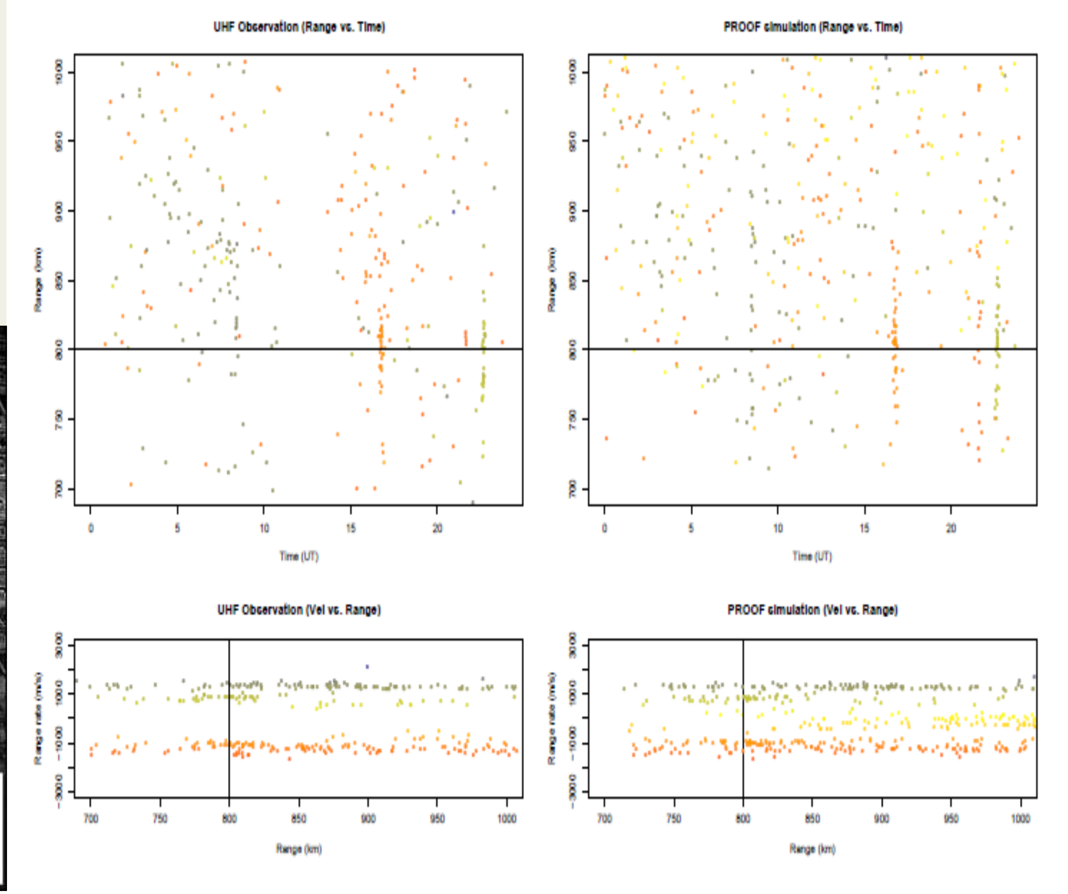


Geospace Environment: Space Debris

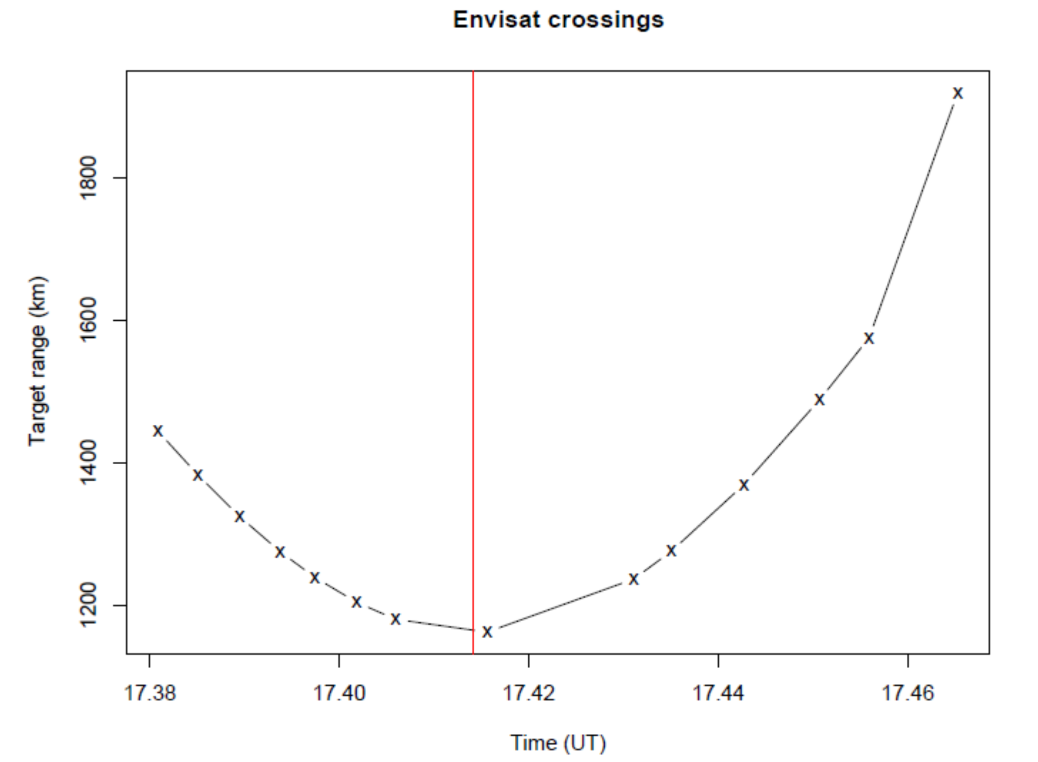


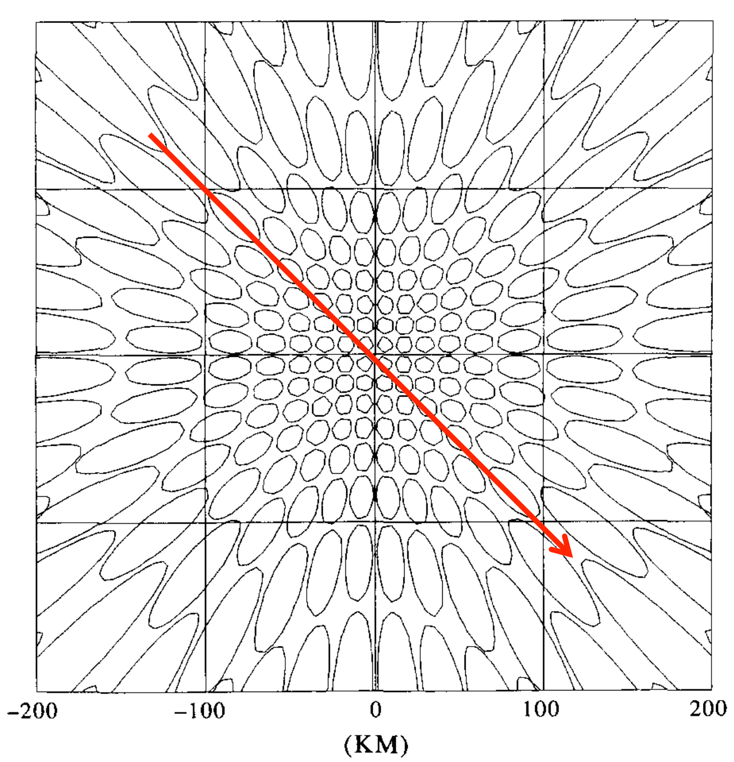






Services: Satellite Tracking

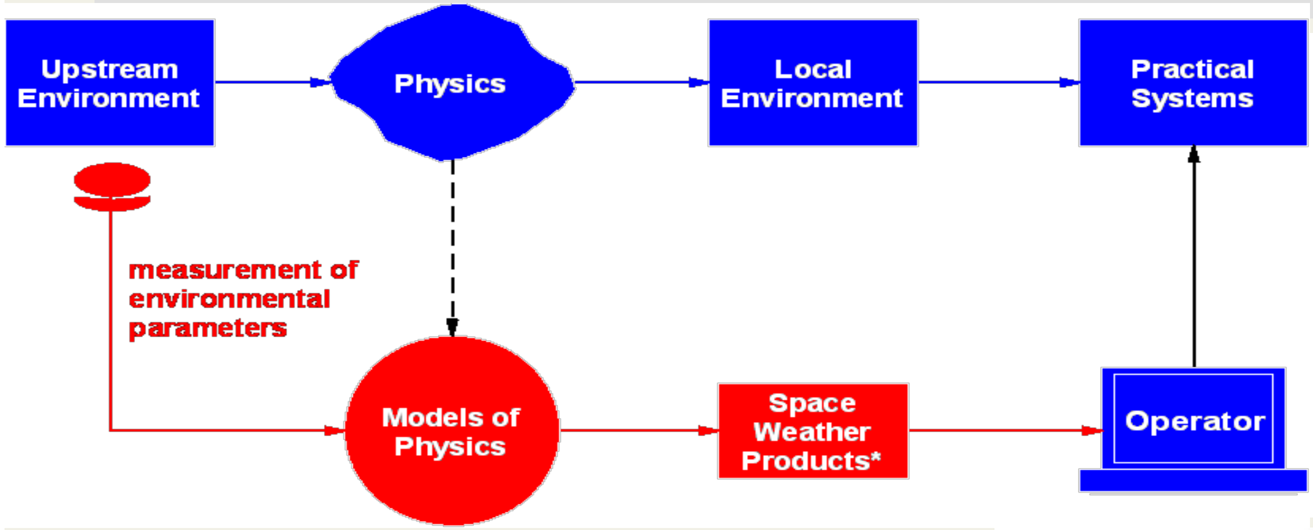


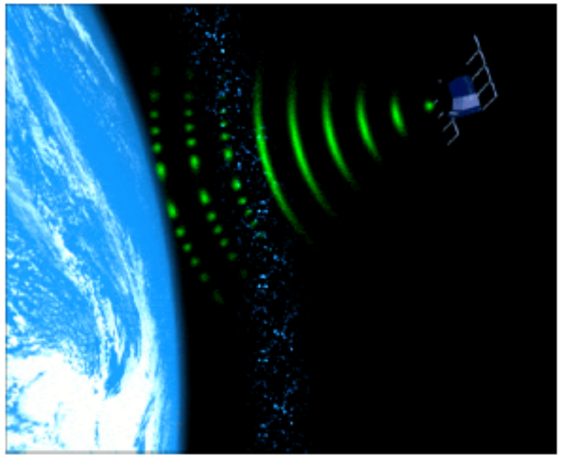


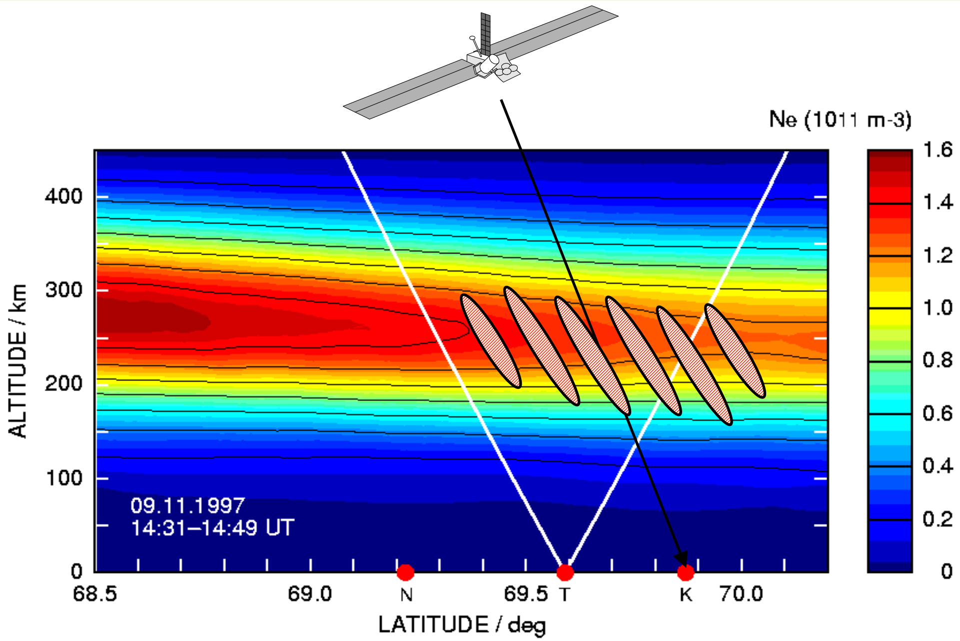
esa space situational awareness

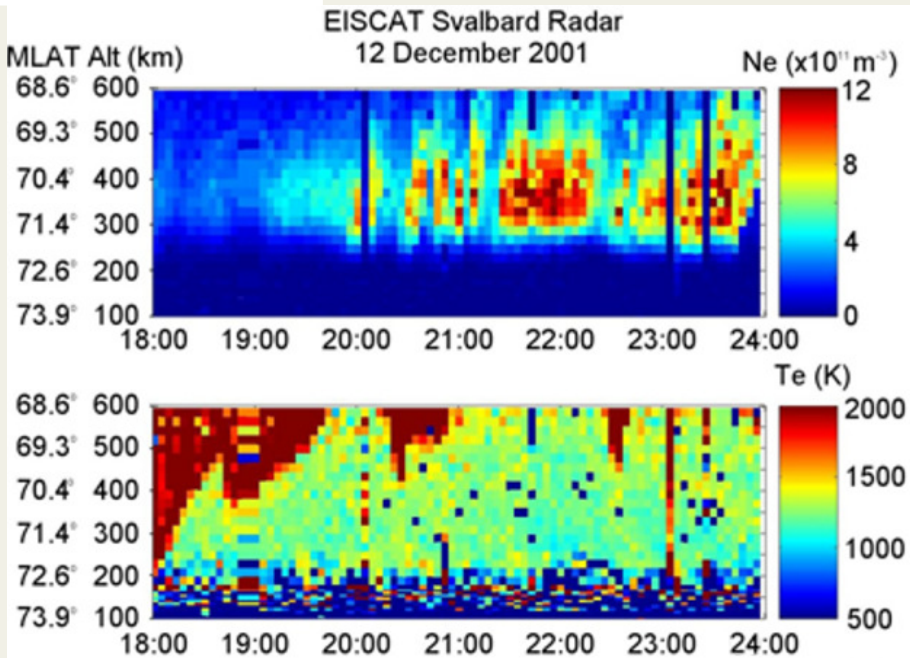
European Space Agency

Services: Positioning and Communications

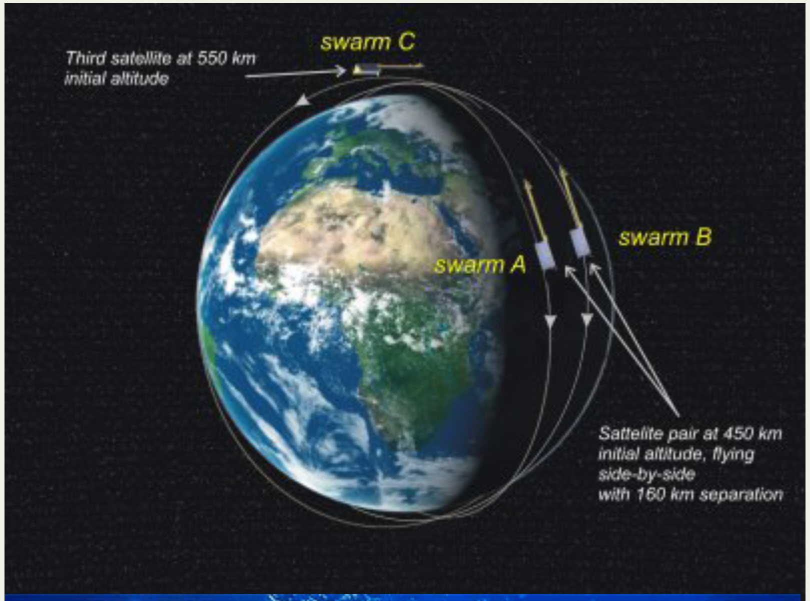


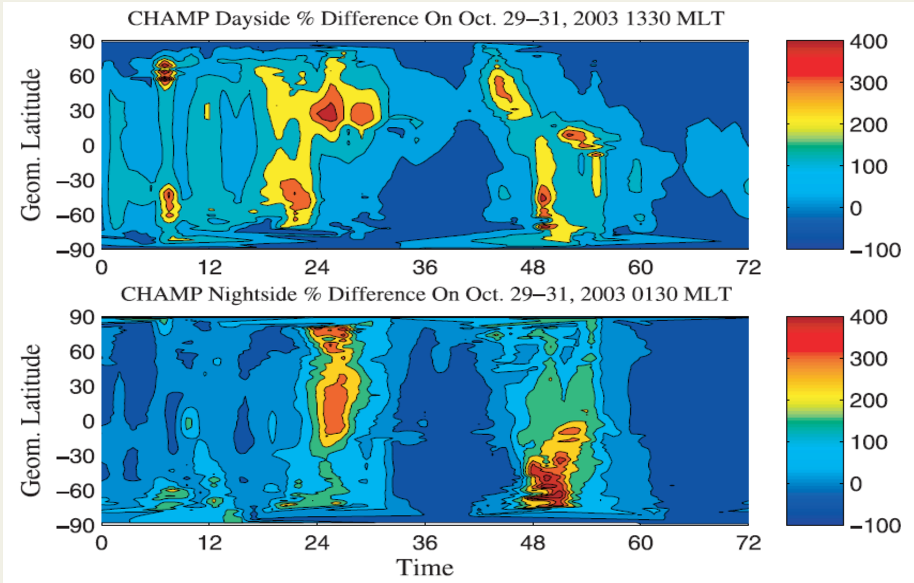


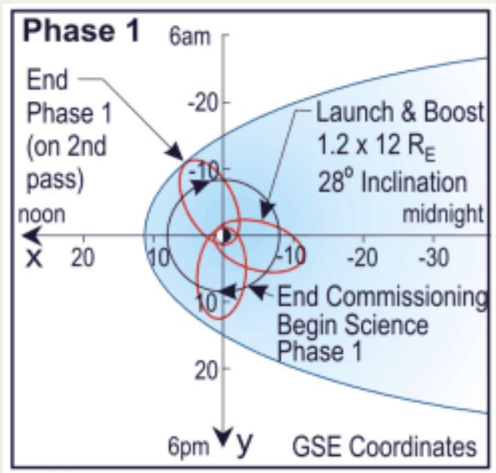


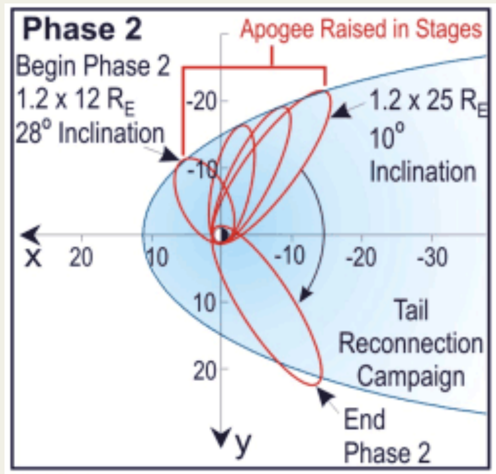


Services: Support for new missions

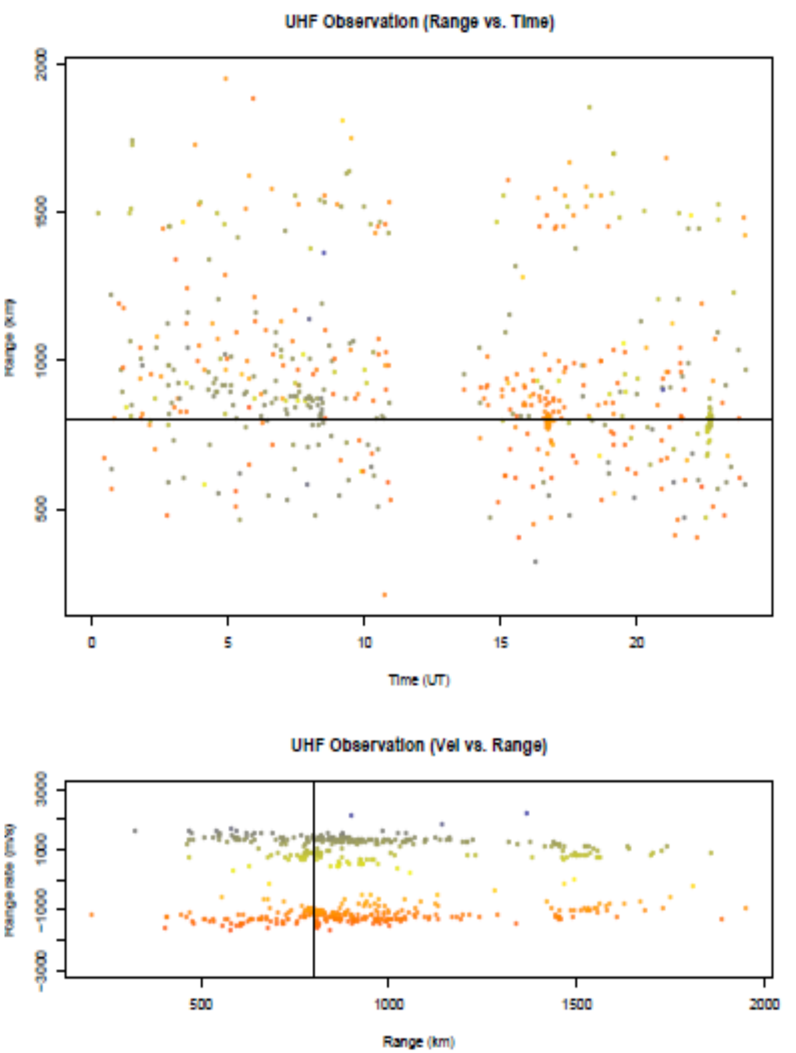


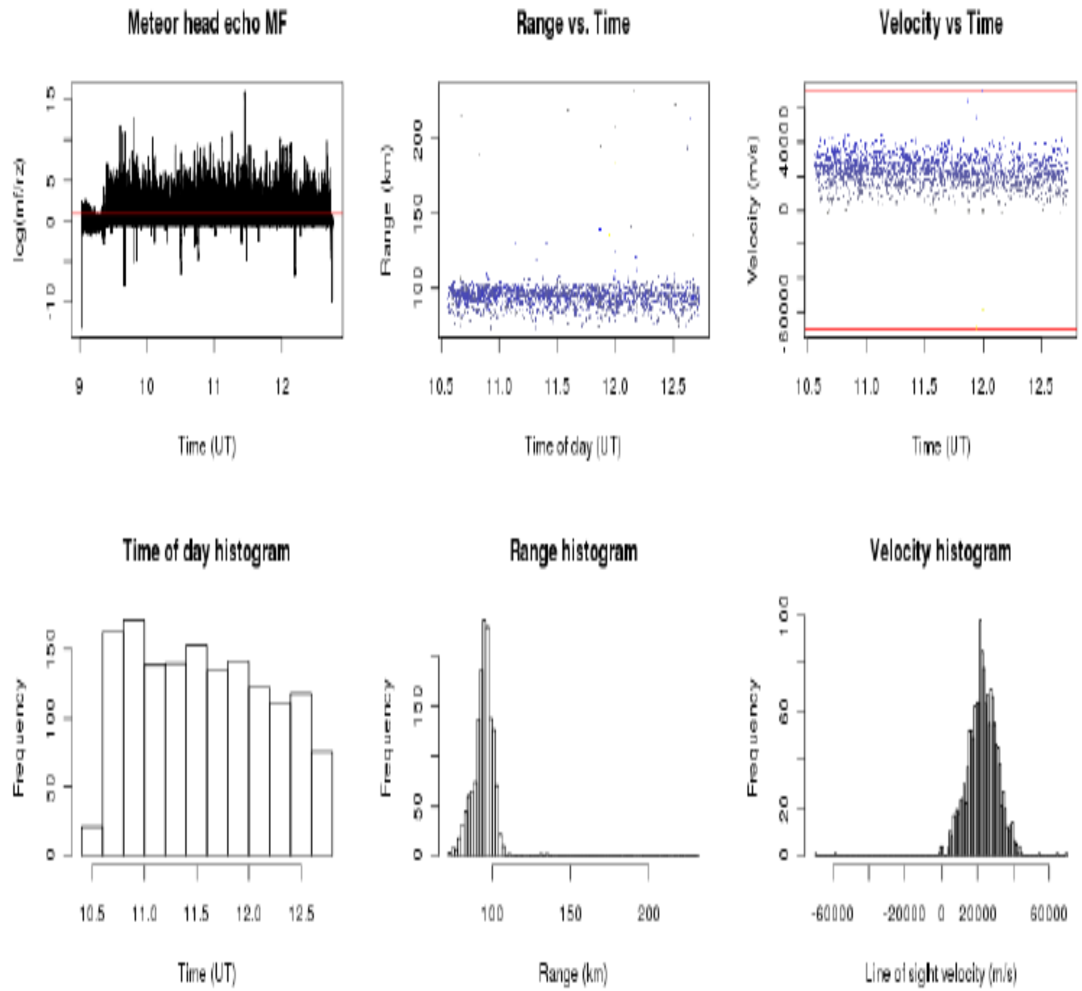




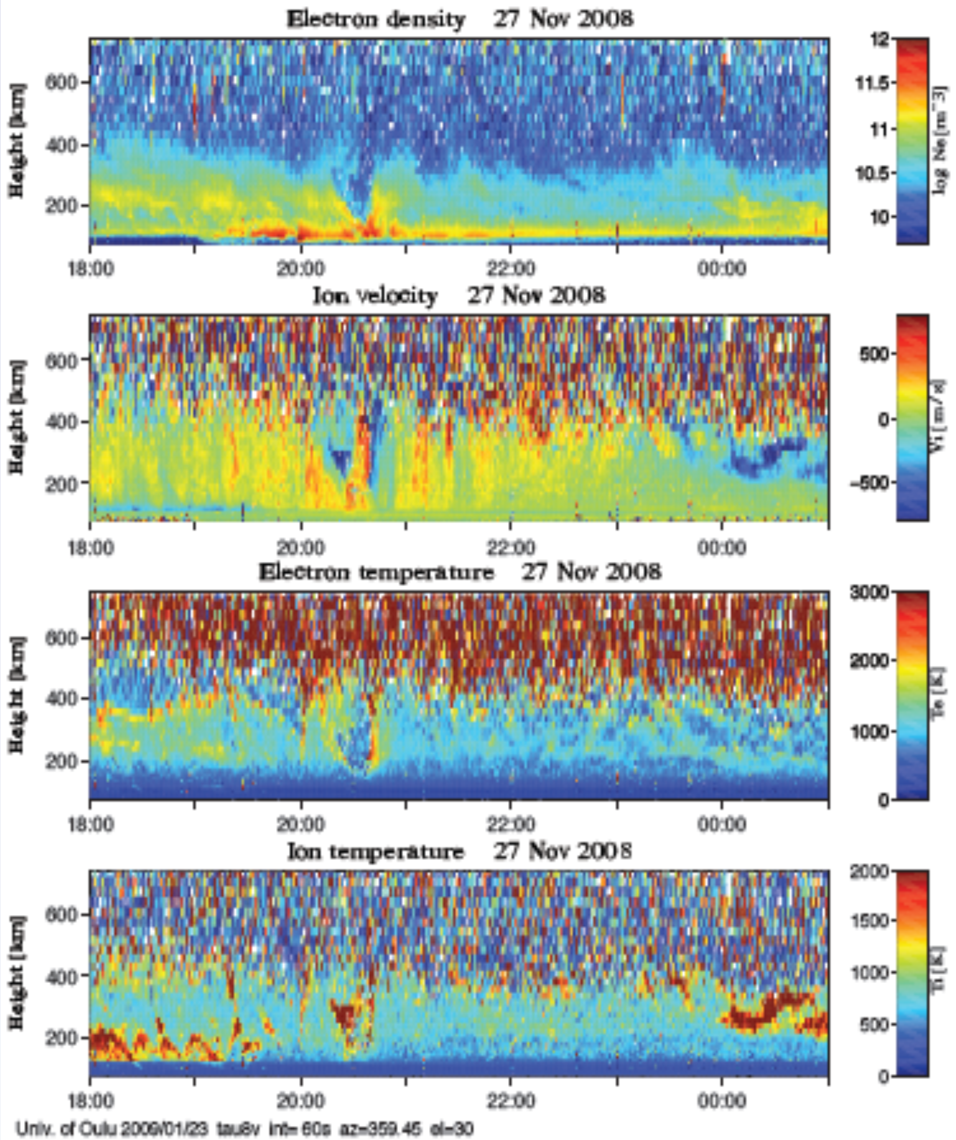


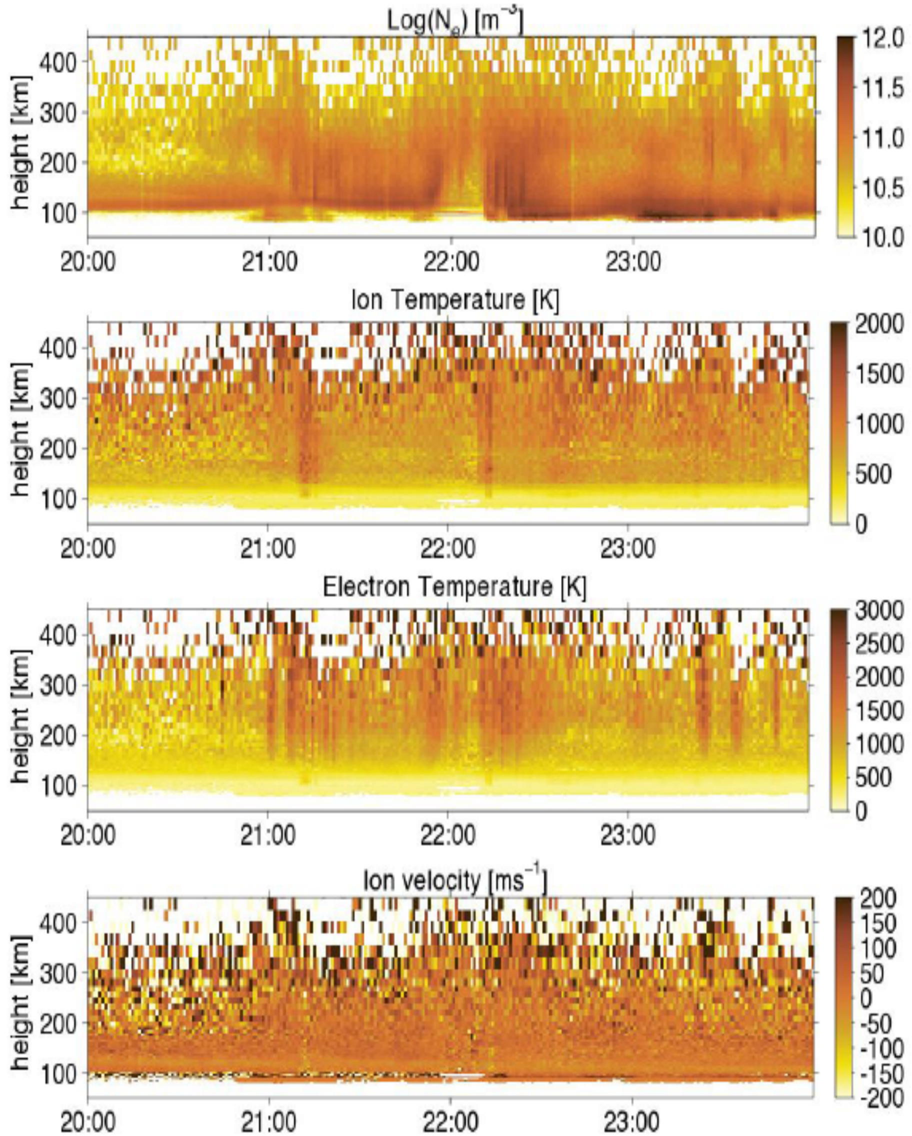
Techniques: New codes and analyses



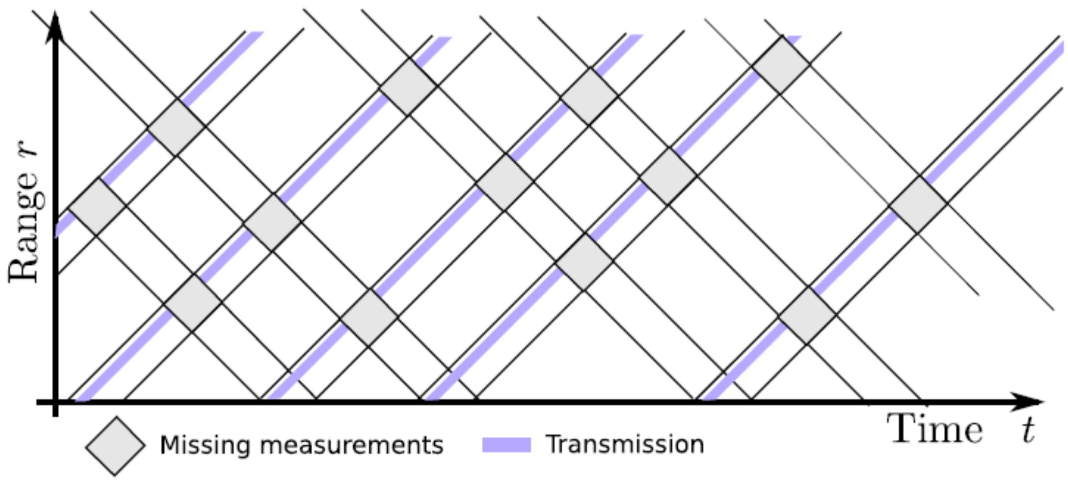


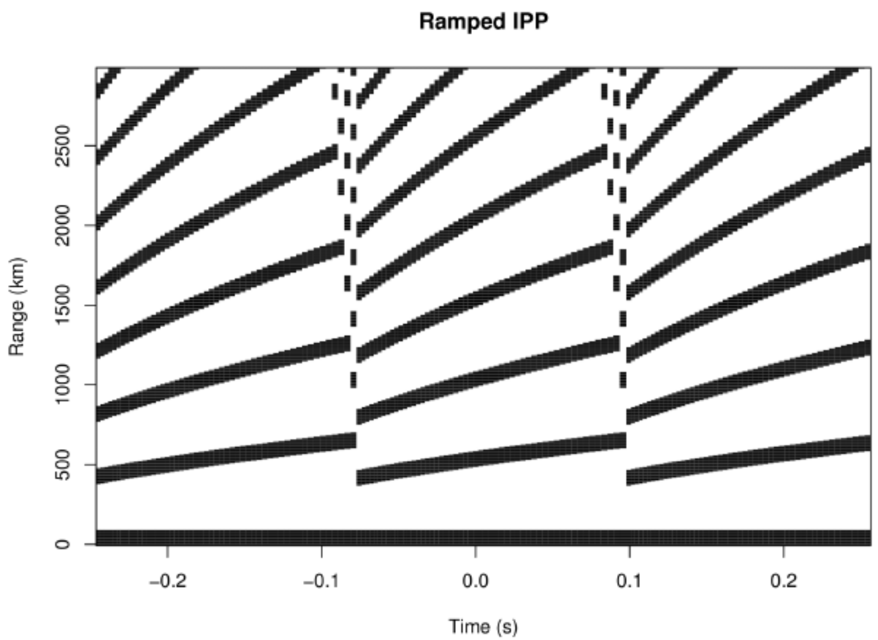
Techniques: New data analysis methods

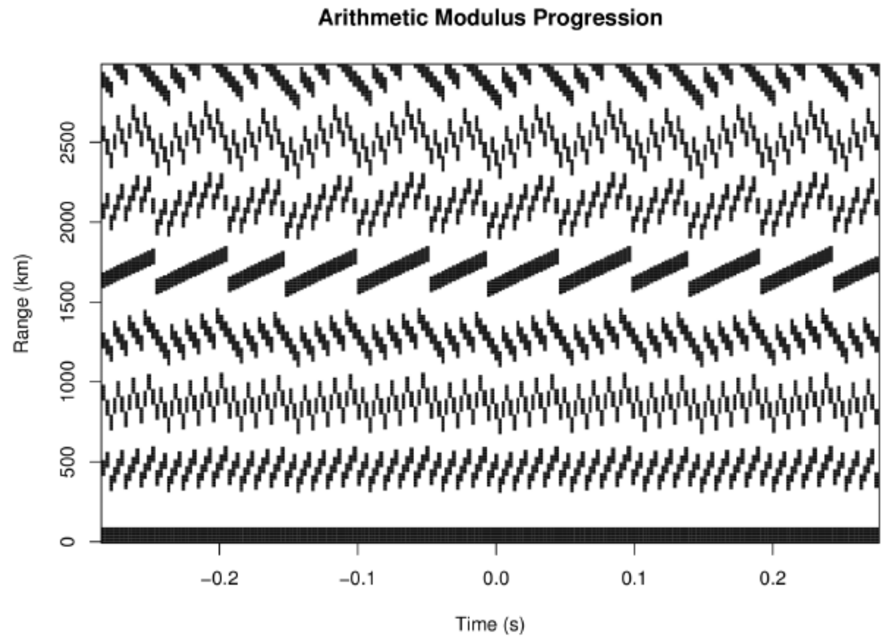




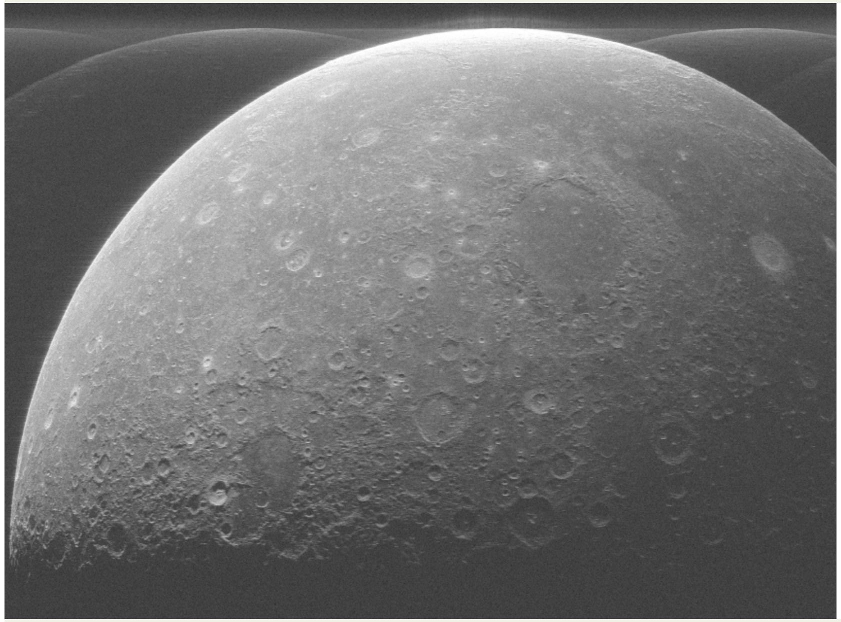
Techniques: Aperiodic and Progressive IPP Codes

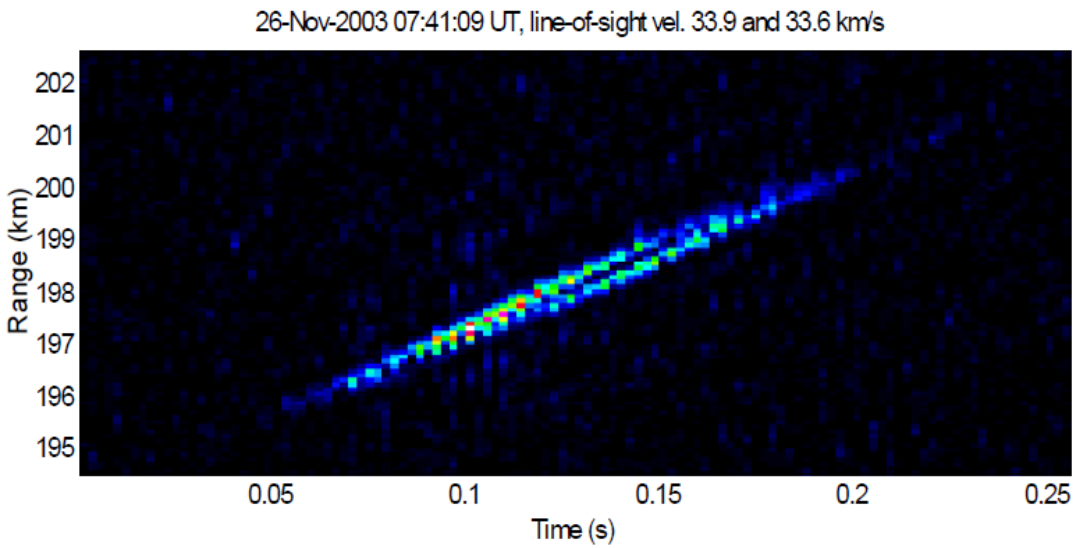


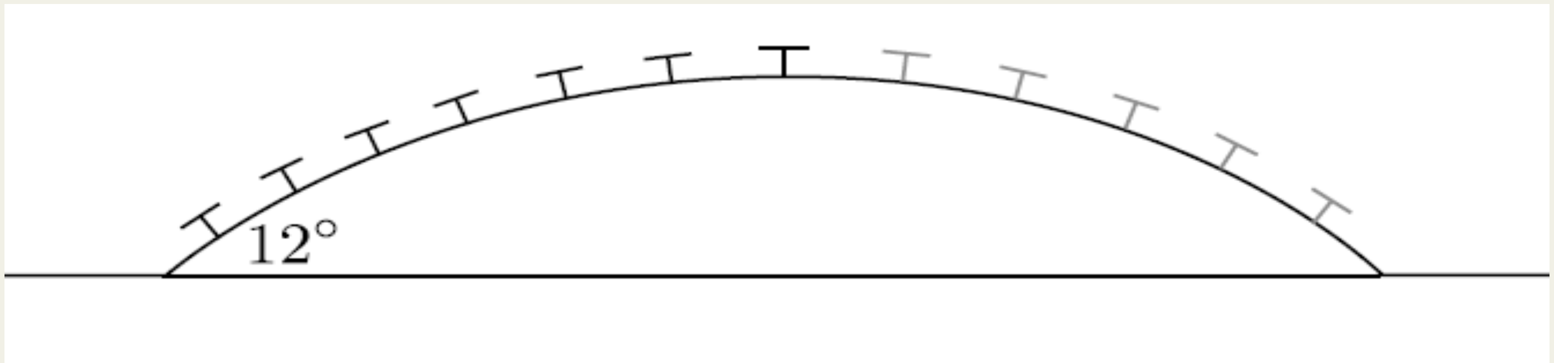




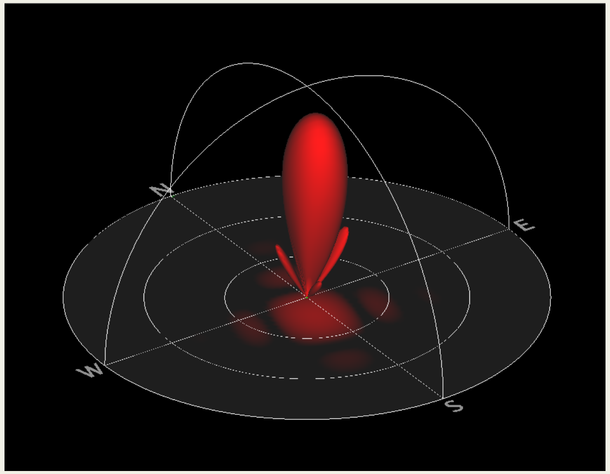
Techniques: Planetary Radar

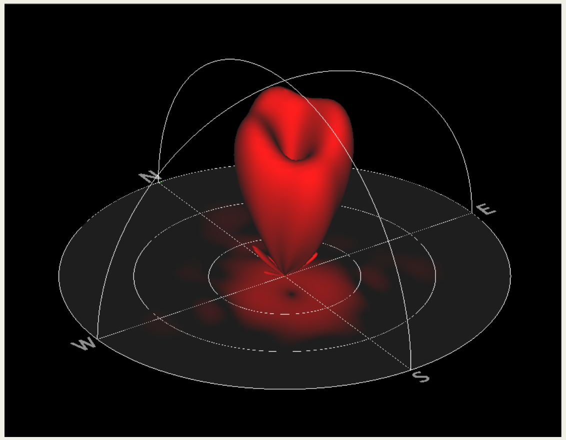


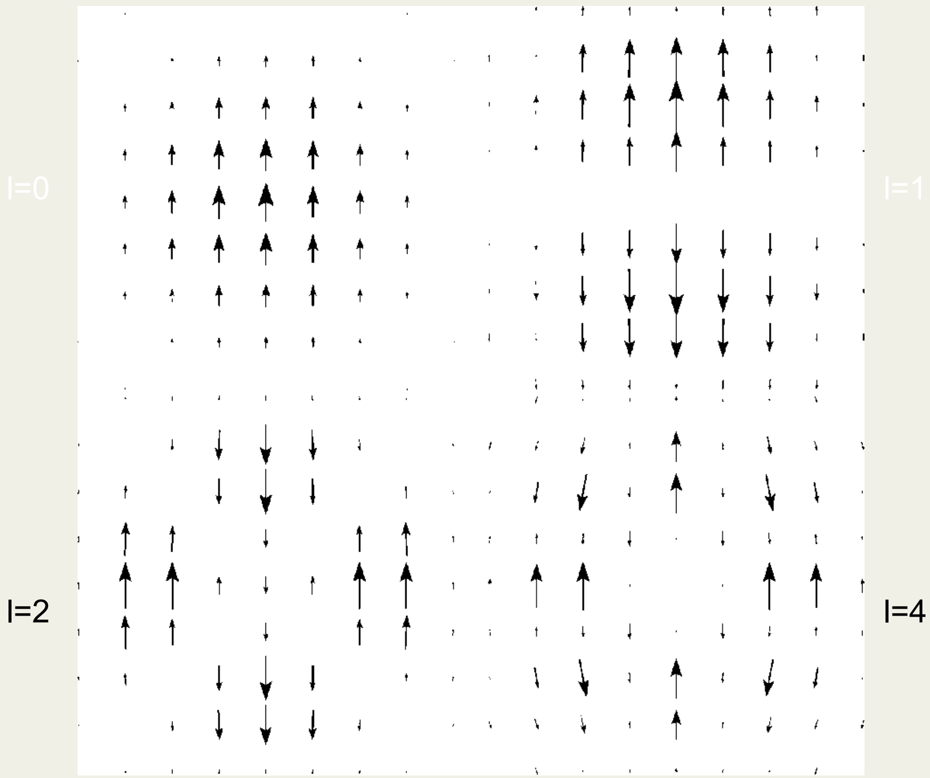




Techniques: Orbital Angular Momentum







(Thidé et al. Phys. Rev. Lett. 99, 087701, 2007)

Experiment Design: Having it all

- EISCAT_3D will re-define the concept of the “EISCAT experiment”
- Instead of a single experiment, we will have general-purpose codes capable of doing several things at once
- We can have multiple interleaved experiments
- We can have adaptive intelligent scheduling
- See Tom Grydeland’s vision at eiscat3d.se

System Design Considerations

The performance of the mainland system is currently governed by the 30-year old TX and antenna systems. To bring it to the level needed to do new cutting-edge science will require order-of-magnitude improvements to essentially all subsystems:

To improve the:	Action required:
transverse resolution	extend the antenna apertures
range resolution	increase the TX power bandwidth
time resolution	increase the effective radiated power, and/or reduce self-clutter…
D/E/topside performance	go to a lower radar frequency
spectrum availability	get a frequency in VHF Band III
E field statistics	set up a better multi-static geometry
spatial **E** field coverage	use phased-arrays and multiple-beam signal processing at remotes
reliability and MTBF	use a phased array also at core site, and solid-state TX modules

Advantages of phased arrays:

- Modularity (allowing gradual upgrades)
- Lightweight mechanics
- No moving parts
- Unified hardware
- Simplified maintenance
- Multi-beaming capability
- Quasi-instantaneous beam steering on transmit
- Routine pointing self-calibration possible
- "Graceful degradation" (up to a point…)

The Debye cutoff: a physical argument for going to a lower frequency

The scattering cross section per plasma electron is $\sigma = \sigma_e \{1 - (1 + \alpha^2)^{-1} + [(1 + \alpha^2)(1 + \alpha^2 + T_e/T_i)]^{-1}\}$, where

$\alpha = 4\pi L_D/\lambda$

L_D is the plasma Debye length and

λ is the radar wavelength.

For $\lambda \gg L_D$ and "normal" T_e/T_i ratios, $\sigma \sim \sigma_e (1 + T_e/T_i)^{-1} \cong (0.2 \,.....\, 0.5)\, \sigma_e$

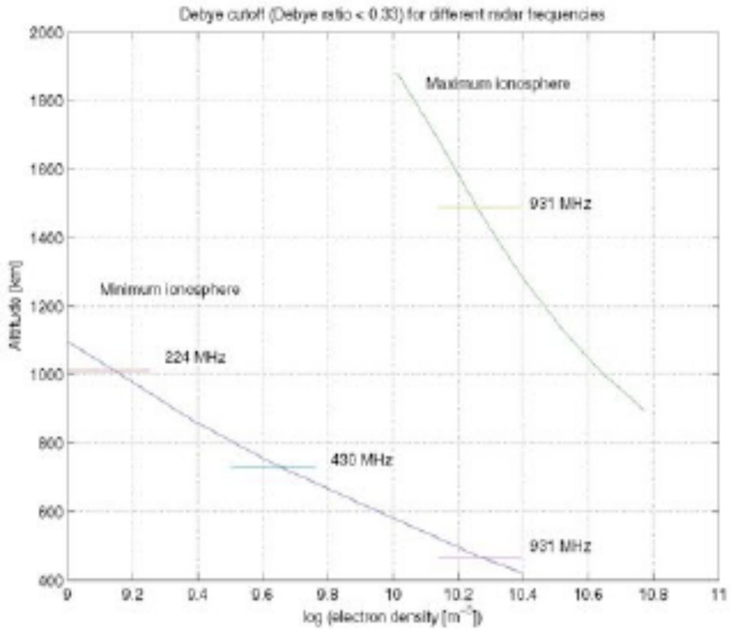
But above 500 km, or below 80 km (in the D region), L_D begins to affect the cross section significantly.

Assuming $T_e/T_i = 1$,

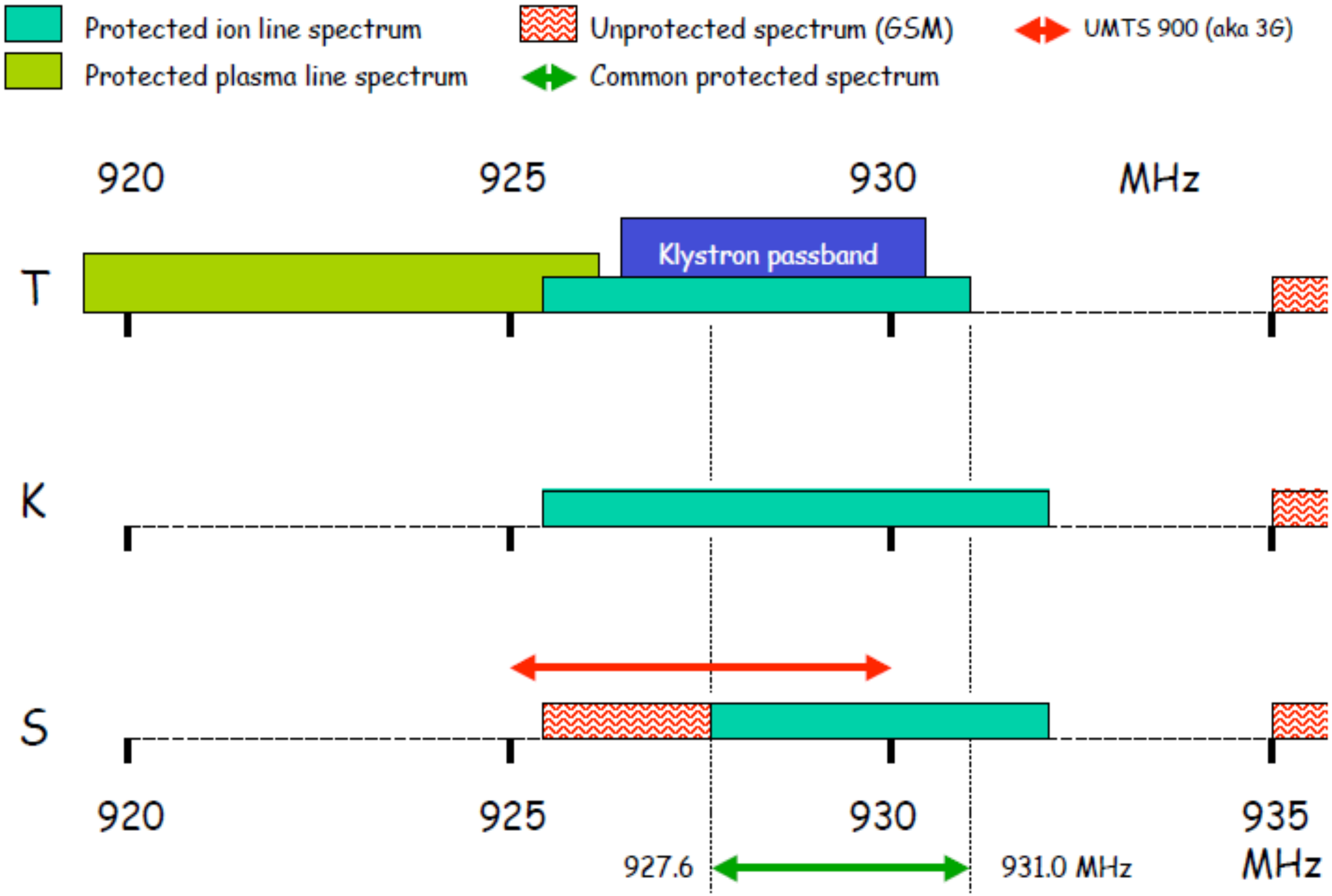
$$\sigma_{ion} (\alpha = 1) = 0.33\, \sigma_{ion} (\alpha = 0)$$

In other words, at very low electron densities the effective radar cross section per electron drops off rapidly. This "Debye cutoff" is a problem for UHF ISR systems. Refer to the graph, where the 33 % - cross section heights are indicated on two typical ionosphere profiles. At 930 MHz, measurements at all heights > 500 km will suffer badly under minimum ionospheric conditions - but a 224 MHz system is still doing fine !

➡ The new radar should be a VHF system !

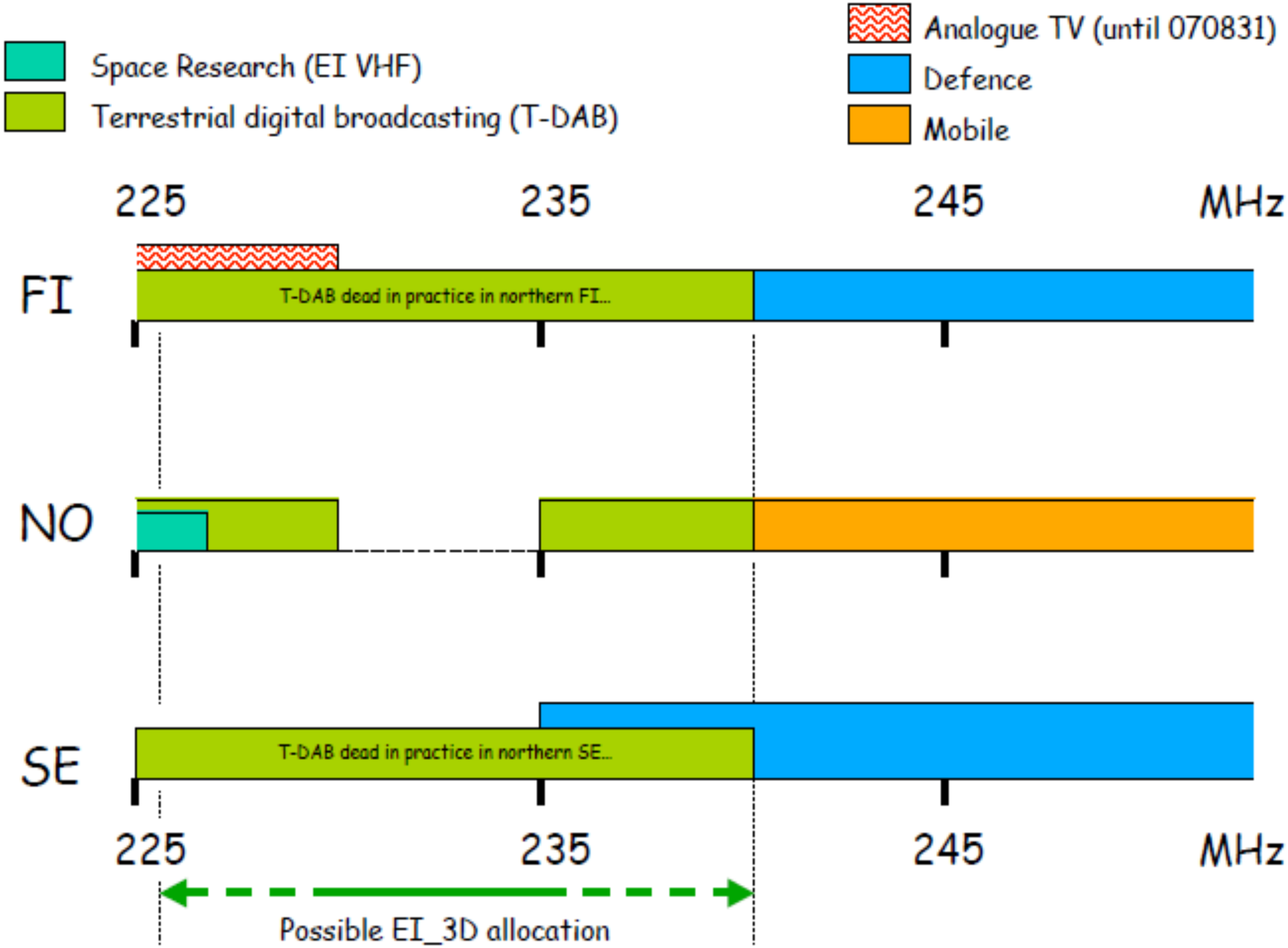


- and a practical argument: the EISCAT UHF Spectrum as of 2007-03



There is a good chance to get a coordinated Nordic VHF allocation for _3D:

Current Use of High VHF Spectrum



EISCAT Scientific Association

Design Study target (from 2005)

- System configuration:
- multiple phased-array ISR
  - **A central transmitting/receiving core facility**, located at, or close to, the EISCAT Tromsø radar.
  - **At least two receiving facilities** for the ionospheric **F1, F2 and topside regions**, located at distances of ~220-280 km south and east.
  - **At least two receiving facilities** for the ionospheric **D and E regions**, at distances of ~90-120 km south and east
  - Data storage and communication systems located at, or close to, each facility.
  - Essentially unattended **continuous operation**.
  - System control, monitoring, data access via Internet.
  - Relative time between sites better than 100 ns, absolute time maintained to GPS/Galileo standards.
  - At central core beam-steering systems for transmission and reception and several (4–10) outlier, receive-only phased-array antennas for in-beam **interferometry.**
  - At **receiving** facilities at least **5 beam formers**

EISCAT 3D Design Specification Document
FP6-2003-Infrastructures-4: EISCAT 3D Proposal #011920

Appendix 1

Tentative EISCAT 3D System Layout

The figure shows one possible layout of the EISCAT 3D system. In this configuration, the central core (denoted by a green filled circle) is assumed to be located near the present Norwegian EISCAT site at Ramfjordmoen. The dashed circle with a radius of approximately 250 km indicates the approximate extent of the field-of-view of the central core at 300 km altitude. Phased-array receiving sites located near Porjus (Sweden) and Kaamanen (Finland) provide 3D coverage over the (250-800) km height range, while two additional receiving sites near Abisko (Sweden) and Masi (Norway) cover the (70-300) km height range.

EISCAT Svalbard Radar

EISCAT_3D Design targets and Central Core Parameters

Radar field-of-view (FOW)

The beam generated by the central core transmit/receive antenna array will be steerable out to a maximum zenith angle of ≈ 40° in all azimuth directions. At 300 km altitude, the radius of the resulting field-of-view is approximately 200 km. In the N-S plane this corresponds to a latitudinal coverage of ± 1.80° relative to the transmitter site.

The antenna arrays at the 3-D receiving facilities will be arranged to permit tri-static observations to be made throughout the central core FOW at all altitudes up to 800 km.

Beam steering

It will be possible to steer the beam from the central core TX/RX antenna array into any one of > 12000 discrete pointing directions, regularly distributed over its FOW and separated by on average 0.625° in each of two orthogonal planes. The beam steering system will operate on a < 500 µs timescale.

Central core parameters:	First phase	Fully instrumented
Number of elements:	16 K	30 K
Diameter [wavelengths]:	87	116
Element separation [wl]:	0.6	0.6
P x A [GW m^{-2}]:	91	295
One-way Half Power BW [degrees]:	0.62	0.46

Cf. the EISCAT VHF system in Mode 1 (full antenna, 3 MW):

P x A = 2.4 GW m^{-2}, HPBW = 0.6 x 1.7 degrees

2.10 Transmitter parameters

Centre frequency:	between 220 – 250 MHz, subject to allocation
Peak output power:	≥2 MW
Instantaneous –1 dB power bandwidth:	≥5 MHz
Pulse length:	0.5-2000 µs
Pulse repetition frequency:	0–3000 Hz
Modulation:	Arbitrary waveforms, limited only by power bandwidth

2.11 Receiver parameters

Centre frequency:	matching the transmitter centre frequency
Instantaneous bandwidth:	±15 MHz
Overall noise temperature:	≤50 K referenced to input terminals
Spurious-free dynamic range:	≥70 dB

2.12 Sensor performance in incoherent scatter mode

The parameters of the different subsystems will be chosen such that, for each of the measurement scenarios tabulated below, the radar will generate estimates of incoherently scattered signal power (or equivalently, uncorrected electron density) with statistical accuracies of better than 10 % in the specified integration times:

Altitude [km]	Electron density [m^{-3}]	T_e/T_i	Ion composition	Height resolution [m]	Integration time [seconds]
80	1 x 10^{9}	1.0		≤100	30
100	3 x 10^{9}	1.0		100	1
150	1 x 10^{10}	1.0	50% NO^+, 50% O^+	100	1
300	3 x 10^{10}	2.0	100% O^+	300	1
800	3 x 10^{10}	3.0	5% H^+, 95% O^+	1000	10
1500	1 x 10^{10}	4.0	10% H^+, 90% O^+		60

2.13 Sensor performance in in-beam interferometer mode

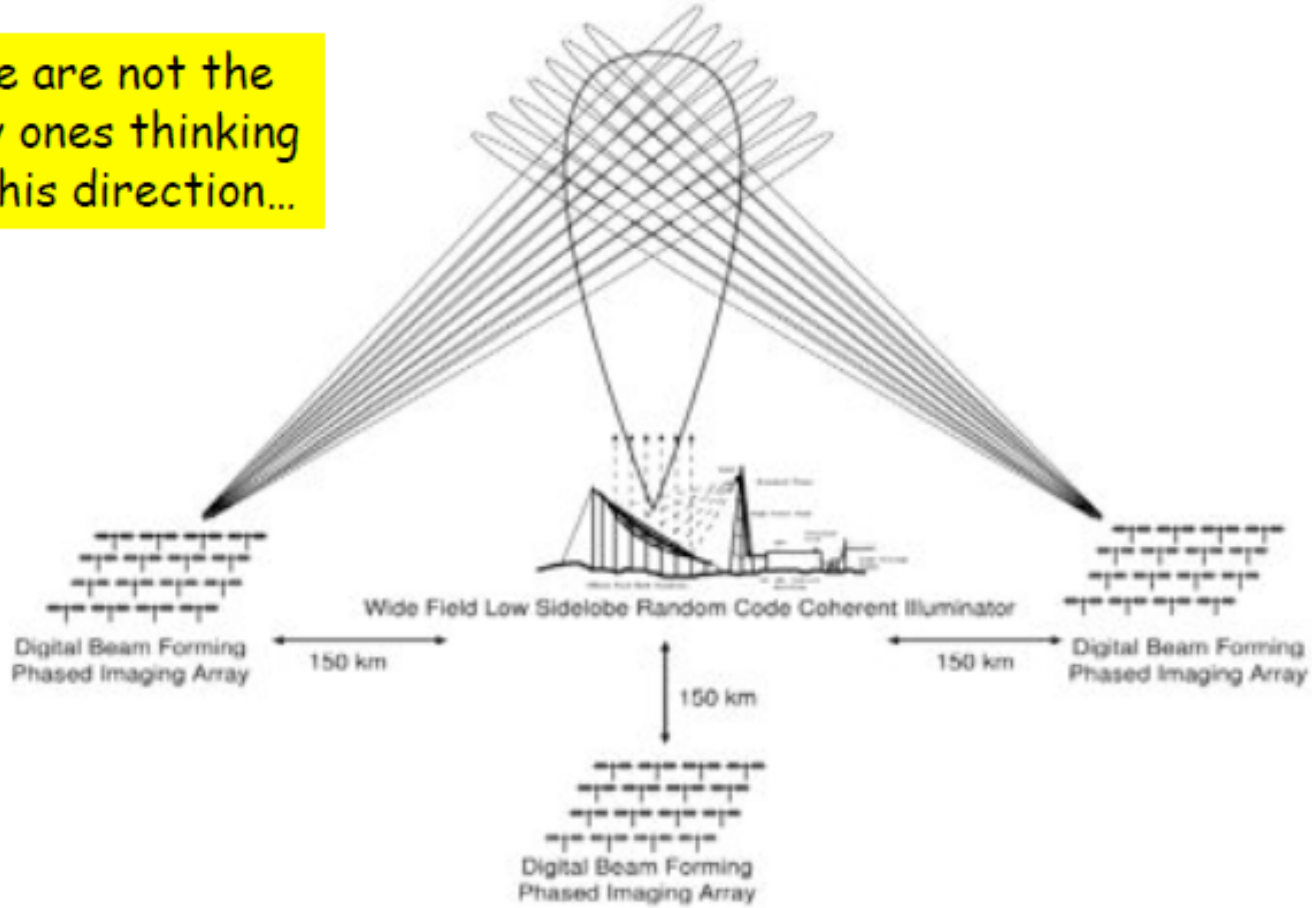
In interferometer mode, the sensor will provide horizontal, 2D resolution of better than 20 m at 100 km altitude.

Improving the system geometry:

- *Core site established close to the present installations at Ramfjordmoen.*
- Finnish site to be moved north, to the vicinity of Inari.
- Swedish site to be moved south, to the vicinity of Porjus.
- Two new "half-way" sites dedicated to D/E work to be established close to the midpoints of the new E-W and N-S baselines.

The Holographic Radar

We are not the only ones thinking in this direction...

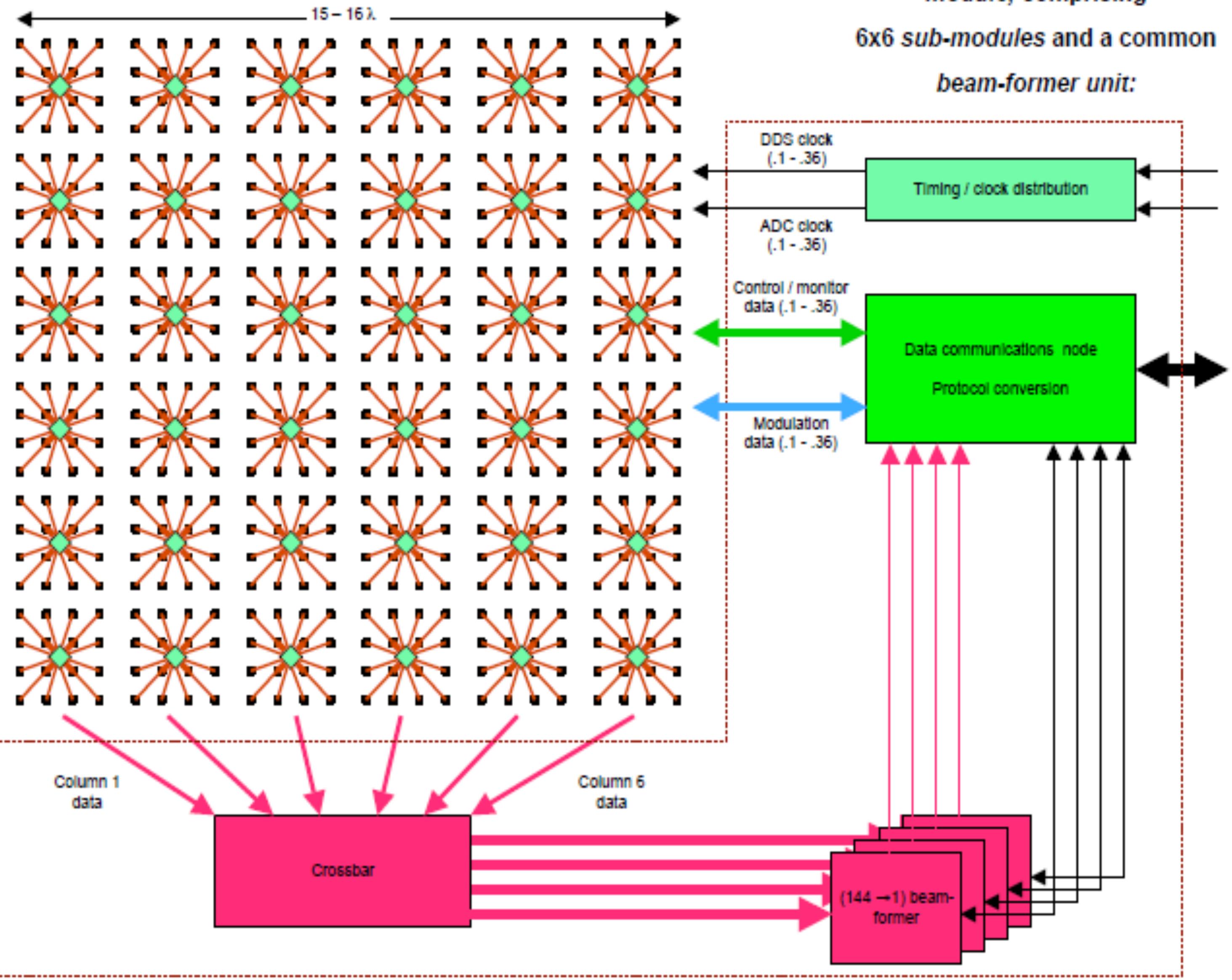


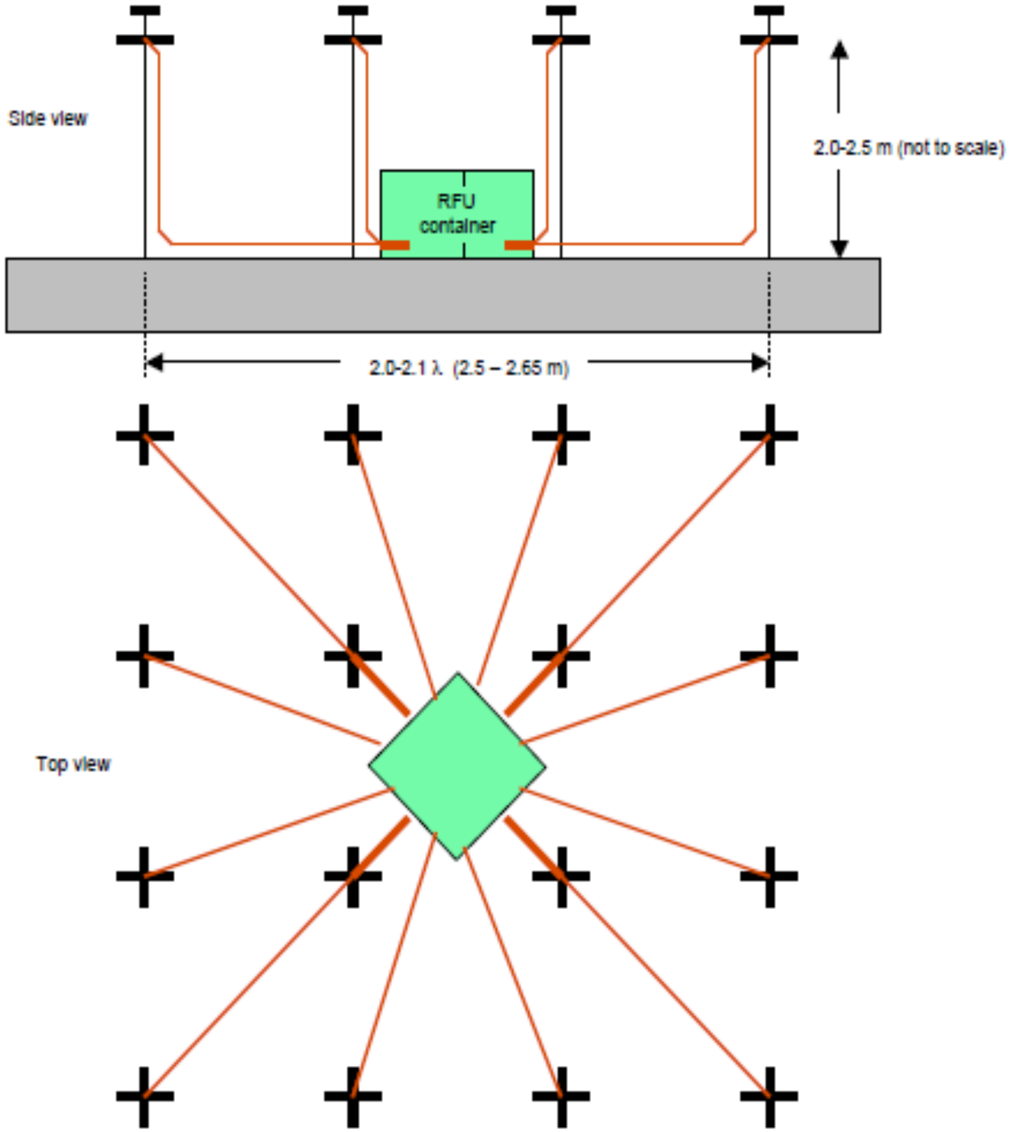
Volumetric ionospheric imaging using a multi-static CW ISR design
Optimal ionospheric measurement of volume and vector quantities
Computationally intensive (petaops)

(Frank Lind, Millstone Hill)

The Core array will be *modular* and *expandable*.

Schematic diagram of a 576-element *module*, comprising 6x6 *sub-modules* and a common *beam-former unit:*



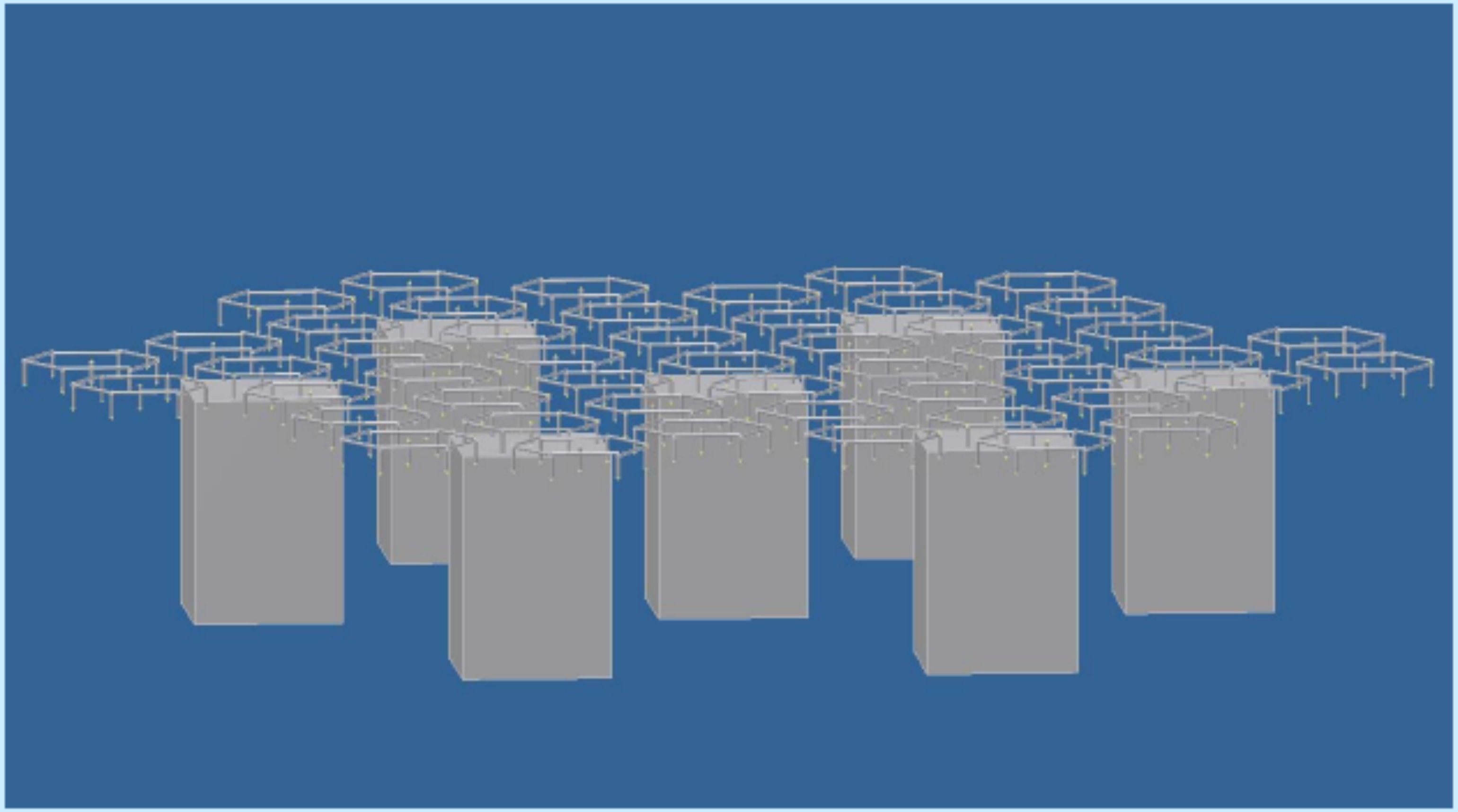


Schematic diagram of a *sub-module*:

16 element antennas + 16-RFU

- The target noise temperature of the 3D receiver, including the T/R switch, is 50 K,
- At 240 MHz, the sky noise temperature at 69º N never drops below 100 K, so the system temperature will always be ≥ 150 K,
- Also, losses in good quality coax cable are fairly low at 240 MHz,
- A run of 5 – 10 m of low-loss coax between each antenna is therefore acceptable, as it adds only 4 – 8 K to the total system temperature and wastes only 3 – 6 % of the transmitted power,
- A relatively large number of RF modules, power supplies and other ancillary equipment can therefore be housed in a common container, situated on the ground underneath the antennas,
- The present design settles on a (4 x 4) element sub-module as being a practical size, as it allows the use of a square section equipment container,
- This brings substantial cost and complexity savings at the sub-module and all higher system levels (16 x fewer weather-proof equipment containers, 16 x fewer power distribution, data networking and time and frequency distribution cables, improved maintenance friendliness etc.).

EI_3D Core Array Side View

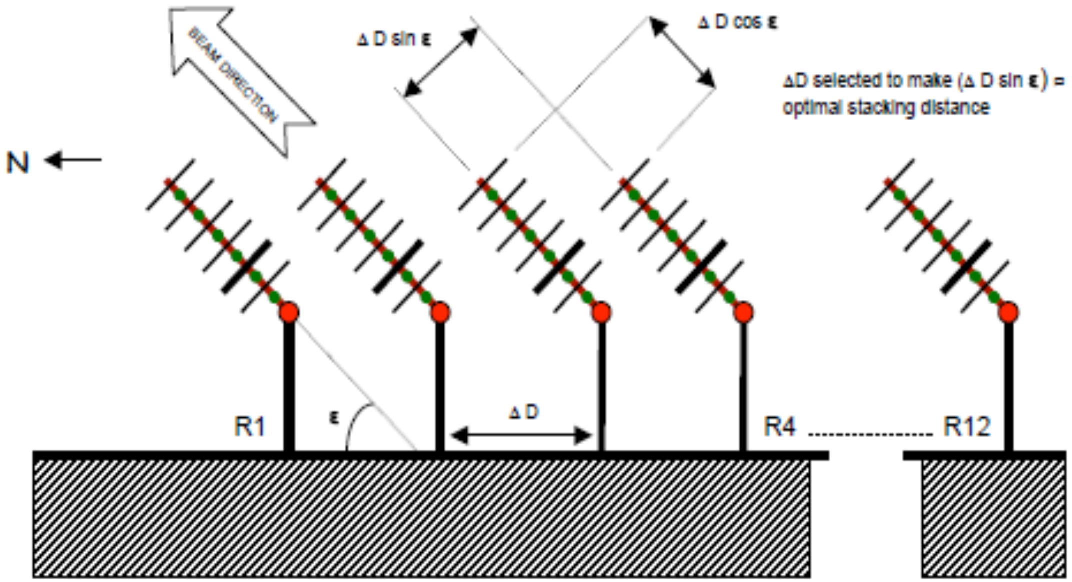


A side view of the 343-element array group. Each hexagon denotes a seven-element cell, comprising six element radiators at its corners and one at its centre. The array is assumed to be elevated at least 3 m above average ground; the actual element radiators and the array support structure are suppressed for clarity. Seven 2 x 2 x 2.8 m equipment containers, each serving 49 radiators, are situated under the array.

The EISCAT_3D Test Array ("Demonstrator")

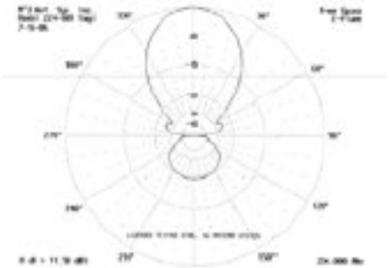
- 200 m² filled array has been erected at the EISCAT Kiruna site to provide facilities for validating several critical aspects of the full-scale 3D "remote" (receive-only) array in practice under realistic climatic conditions:
  - Receiver front ends, A/D conversion (WP 4),
  - SERDES, copper/optical/copper conversion (WP 12),
  - Time-delay beam-steering (WP4 / WP9),
  - Simultaneous forming of multiple beams (WP 9),
  - Adaptive pointing (self-) calibration (WP 9),
  - Adaptive polarisation matching (WP 9),
  - Interferometry trigger processor (WP 5),
  - Digital back-end / correlator for standard IS (WP 9),
  - Time-keeping (WP12)

- Array oriented in Tro-Kir plane; 48 short (6+6) element Yagis at 55° elevation,
- Center frequency of (224 ± 3) MHz allows reception of transmissions from existing Tromsø VHF system. SNR estimated to be sufficient for useful bistatic IS work (> 6% @ 300 km, 1.0 10^{11} m^{-3}),
- The 55° elevation provides coverage from ~ 200 km altitude to over 800 km above Tromsø.

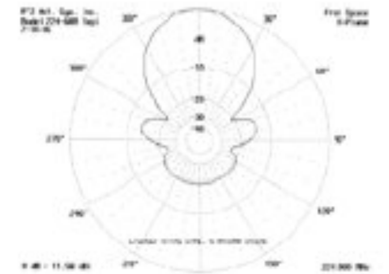


Demonstrator element antennas

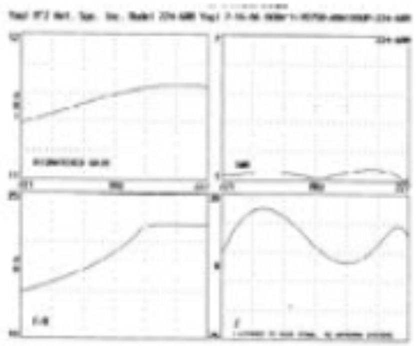
48 short, 224-6RM (6+6) element X yagi antennas for (224 ± 3) MHz purchased from M2 Inc. Fresno, CA.



E plane pattern

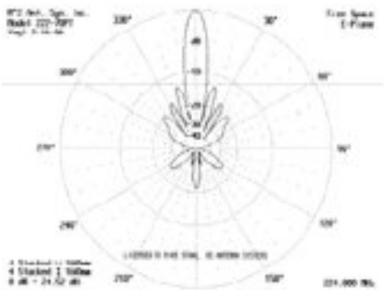


H plane pattern



Gain and VSWR vs. frequency

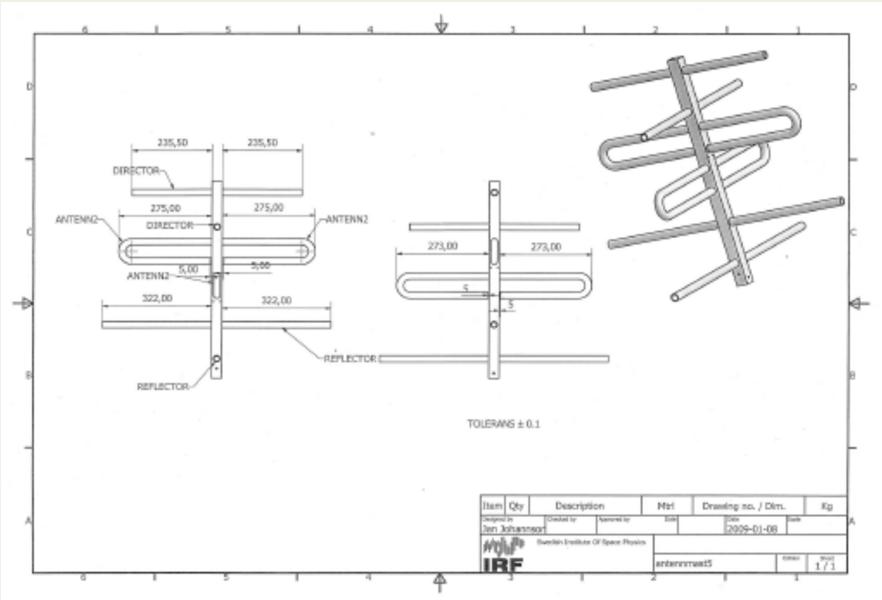
Initially, signals from the four antennas in each row will be directly combined in-phase and beam-steering implemented only in the N-S elevation plane:



E plane pattern
(four antennas,
stacked broadside)

The first two element antennas assembled and installed, autumn 2006

EISCAT_3D Antennas



- The "Renkwitz Yagi"
- Centre frequency 235 MHz
- Bandwidth 12 MHz (>20 dB)
- Opening angle 40^o (core array), 30^o (receiver arrays)
- Arbitrary polarisation
- Good sidelobe supression

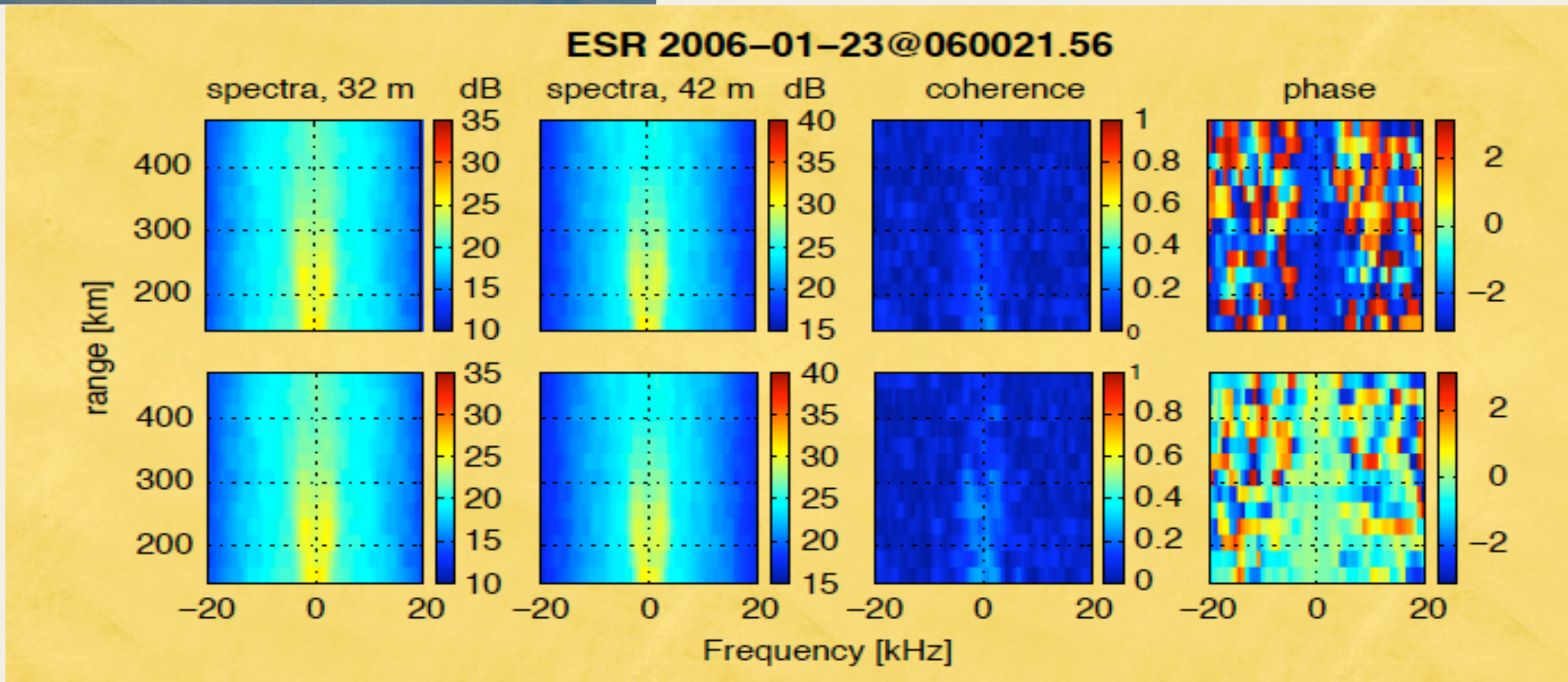
- 7dB gain over 10% relative bandwidth
- Need to be mechanically robust (e.g. due to snow loading)
- Bandwidth should not be affected by icing
- Mutual coupling needs to be acceptable

Imaging and Interferometry

Imaging concept already developed by UiT on the ESR system

Extended to aperture synthesis imaging

Specified for an EISCAT_3D type



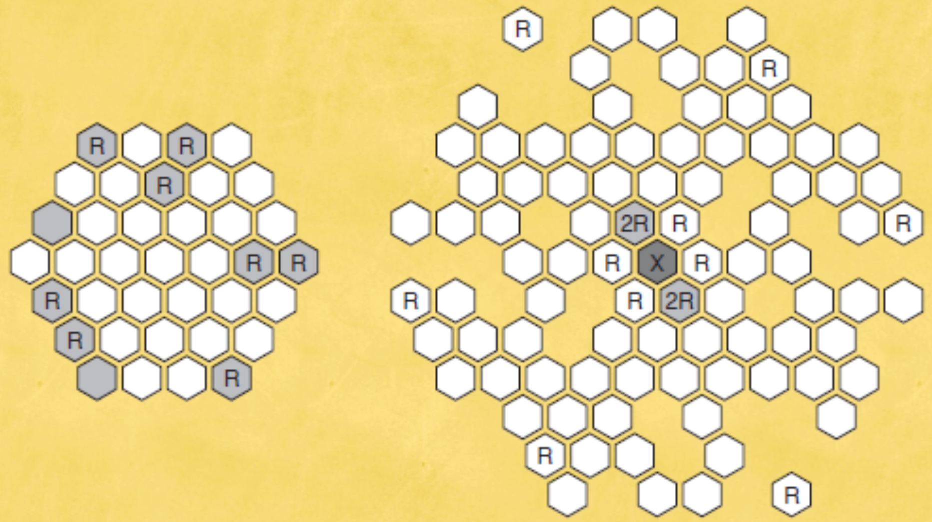
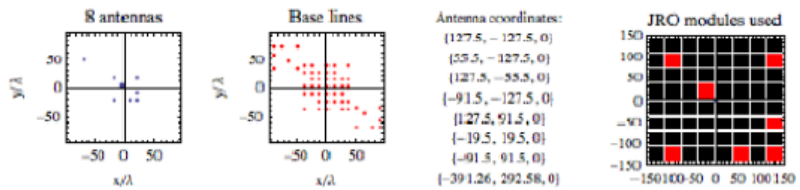
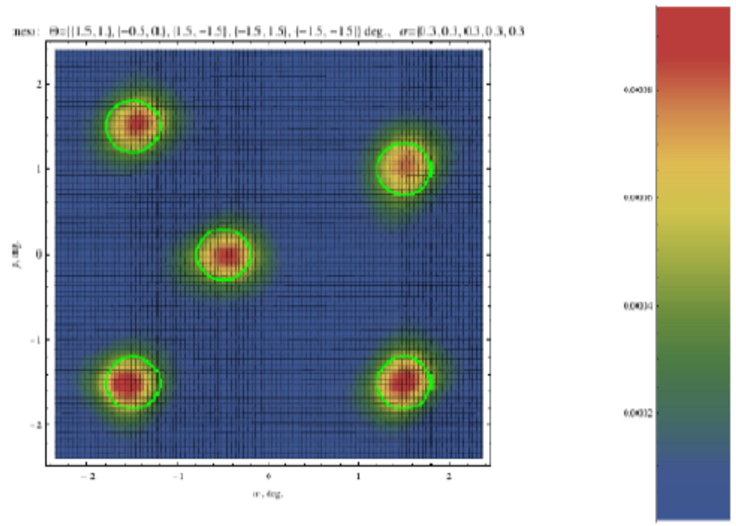
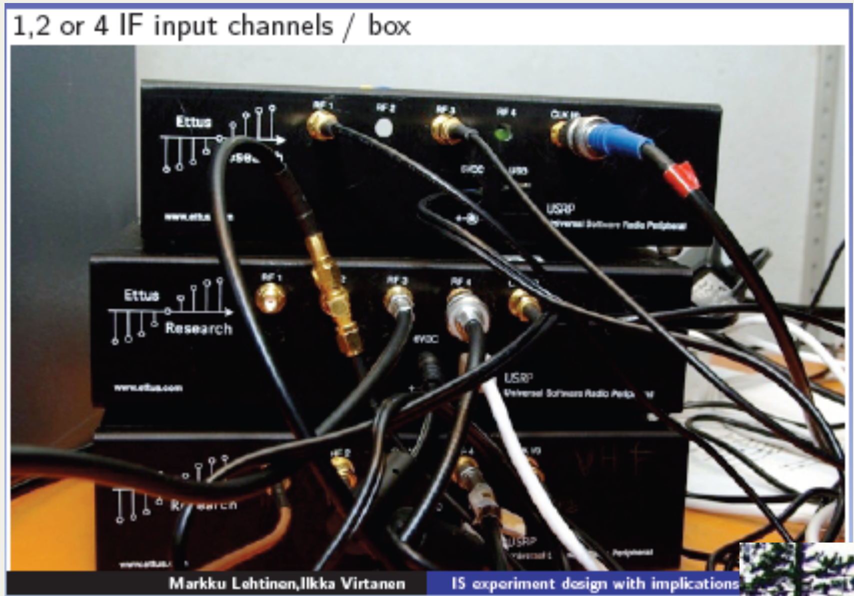


Figure 1: A core antenna implemented with 37 hexagonal modules showing a 10-module configuration (shaded hexagons on the right side) that achieves 44 non-redundant baselines and one repeated. The baselines are shown on the right side with the redundant baselines shaded. The modules marked with an “R” are the suggested for real time monitoring.





EISCAT_3D Signal Processing



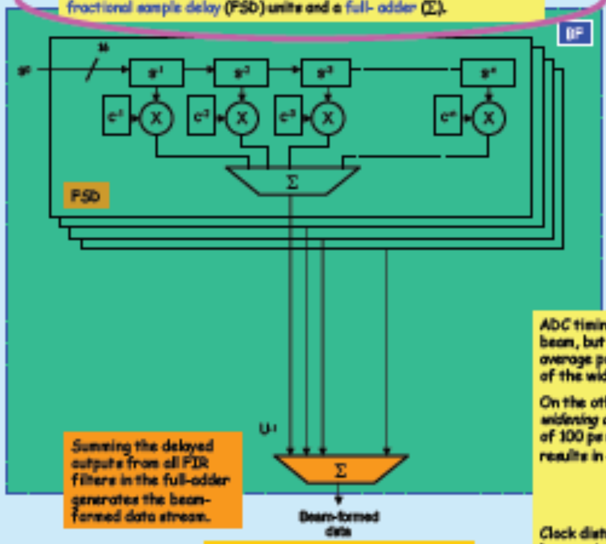
Design study did not specify a chosen system due to speed of evolution in DSP technology

Preparatory phase will evaluate the use of multi-channel samplers and high performance computing for DSP and beam-forming

EISCAT_3D technology can be prototyped on a range of different systems, e.g. the MST radar at Sodankyla.

Digital beam-forming, multi-beaming and beam errors

A digital beam-former (BF) consists of two main parts, viz. a set of fractional sample delay (FSD) units and a full-adder (Σ).



One FSD unit is required per element antenna and beam. It can be realised as a generic FIR filter structure in FPGA logic.

The coefficients c_m, m= 1..n, determine the filter group delay and must be computed for each element antenna and beam direction.

Summing the delayed outputs from all FIR filters in the full-adder generates the beam-formed data stream.

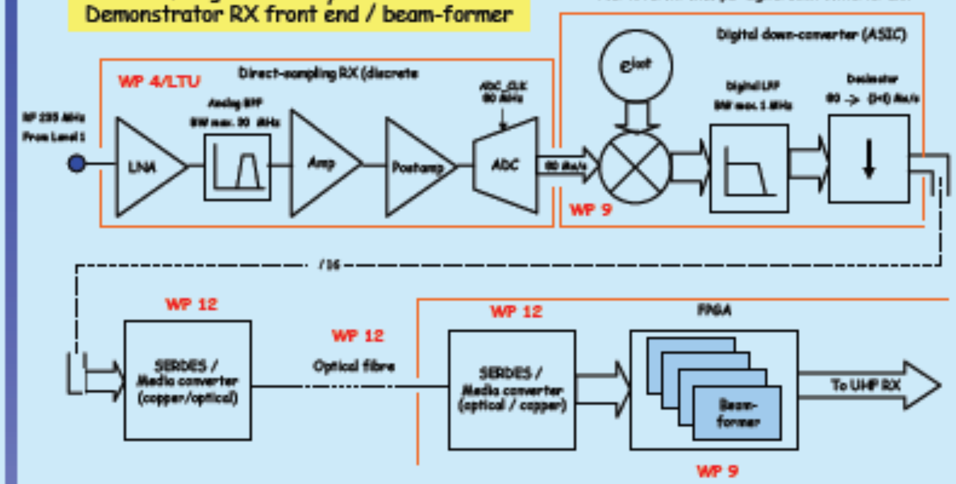
Multiple beams can be generated from the same data by simply adding more beam-formers, one per beam!

ADC timing jitter and other timing errors affect the beam, but when the error distribution is Gaussian, the average pointing direction stays the same regardless of the width of the distribution.

On the other hand, *Gaussian timing jitter causes a widening of the beam and a loss of gain.* A 3-σ jitter of 100 ps results in a 0.1 dB gain loss; 500 ps jitter results in almost 2 dB gain loss!

Clock distribution and ADC sampling stabilisation now become important issues; in order not to lose performance, the system must be designed for a 3-σ jitter of less than 100 ps, array-wide.

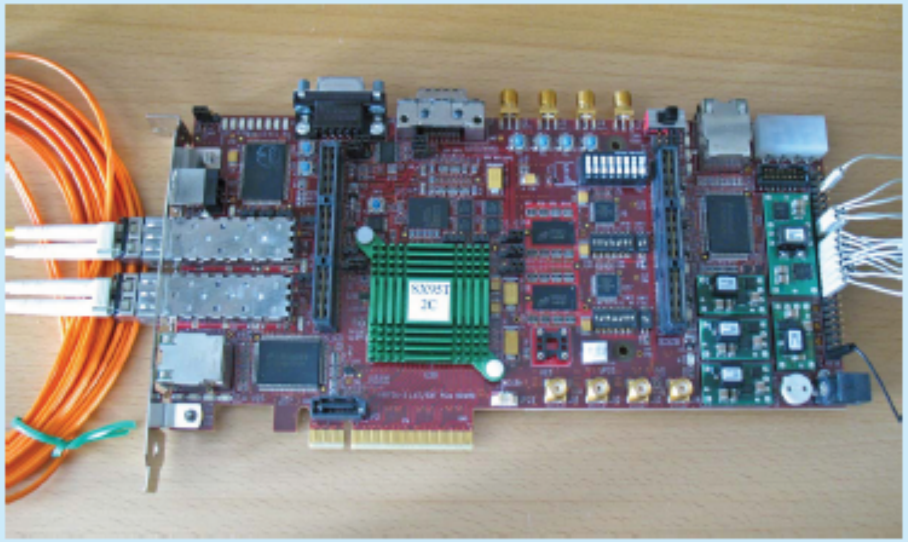
Block diagram of fully instrumented Demonstrator RX front end / beam-former

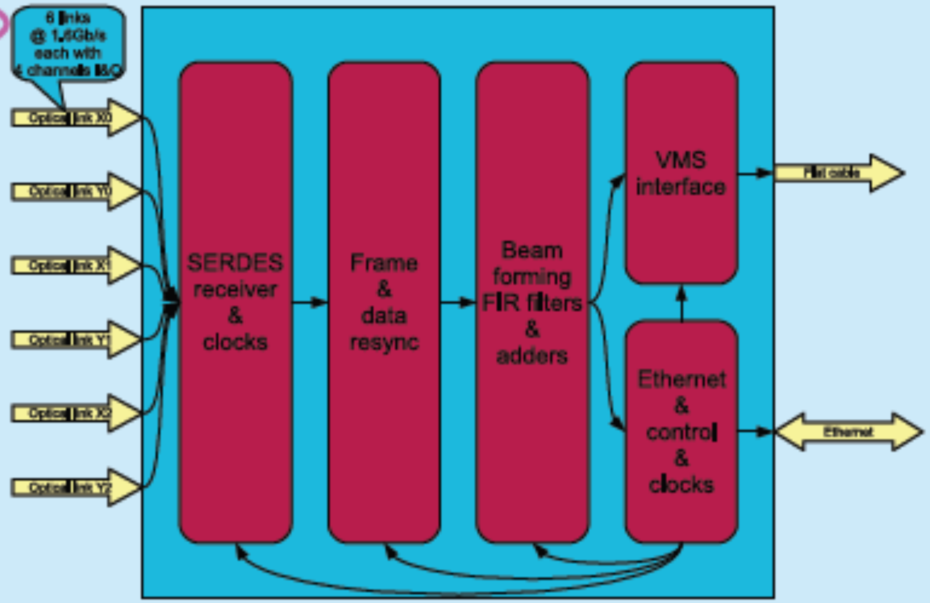


This architecture was adopted to get the Demonstrator array operational as quickly as possible:

- The digital down-converter unit band-limits the 30 MHz front end signal to 1 MHz, enough for ion line work,
- Decimated data from all rows is serialised, media-converted and transferred on optical fibre to the site control room,
- Multiple beam-former processes running in an FPGA combine signals from all rows into beam-formed data streams,
- These are fed into the existing UHF receiver channel boards and processed normally by lag_wrap under eros.

How the FIR filters are realised in practice: FPGA technology





from: G. Wannberg: Uppsala, Sweden 28.5.2009

Radar

EISCAT_3D Transmitters

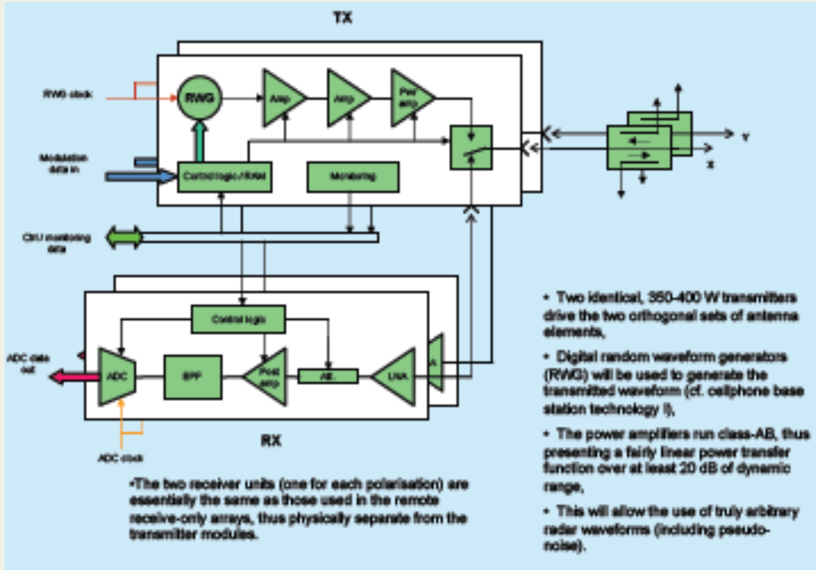
Centre frequency 220-250 MHz

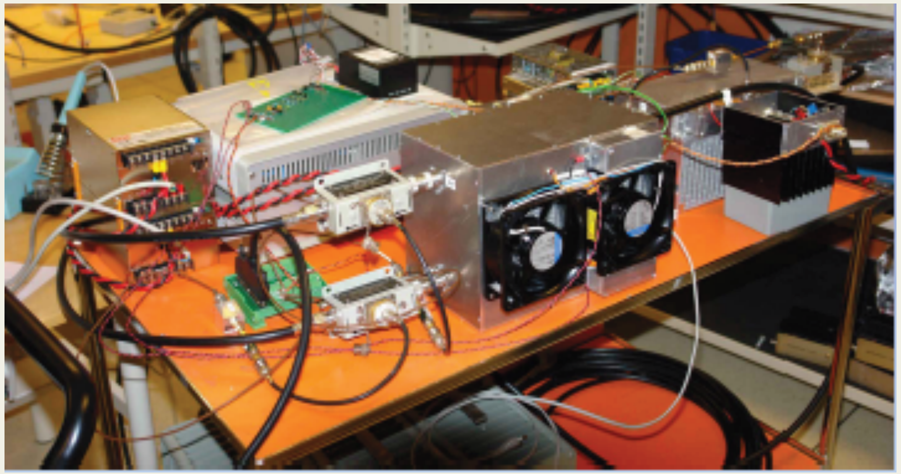
Peak output power > 2 MW

-1 dB power bandwidth > 5 MHz

Pulse length 0.5 to 2000 us

Pulse repetition frequency 0 to 3000 Hz

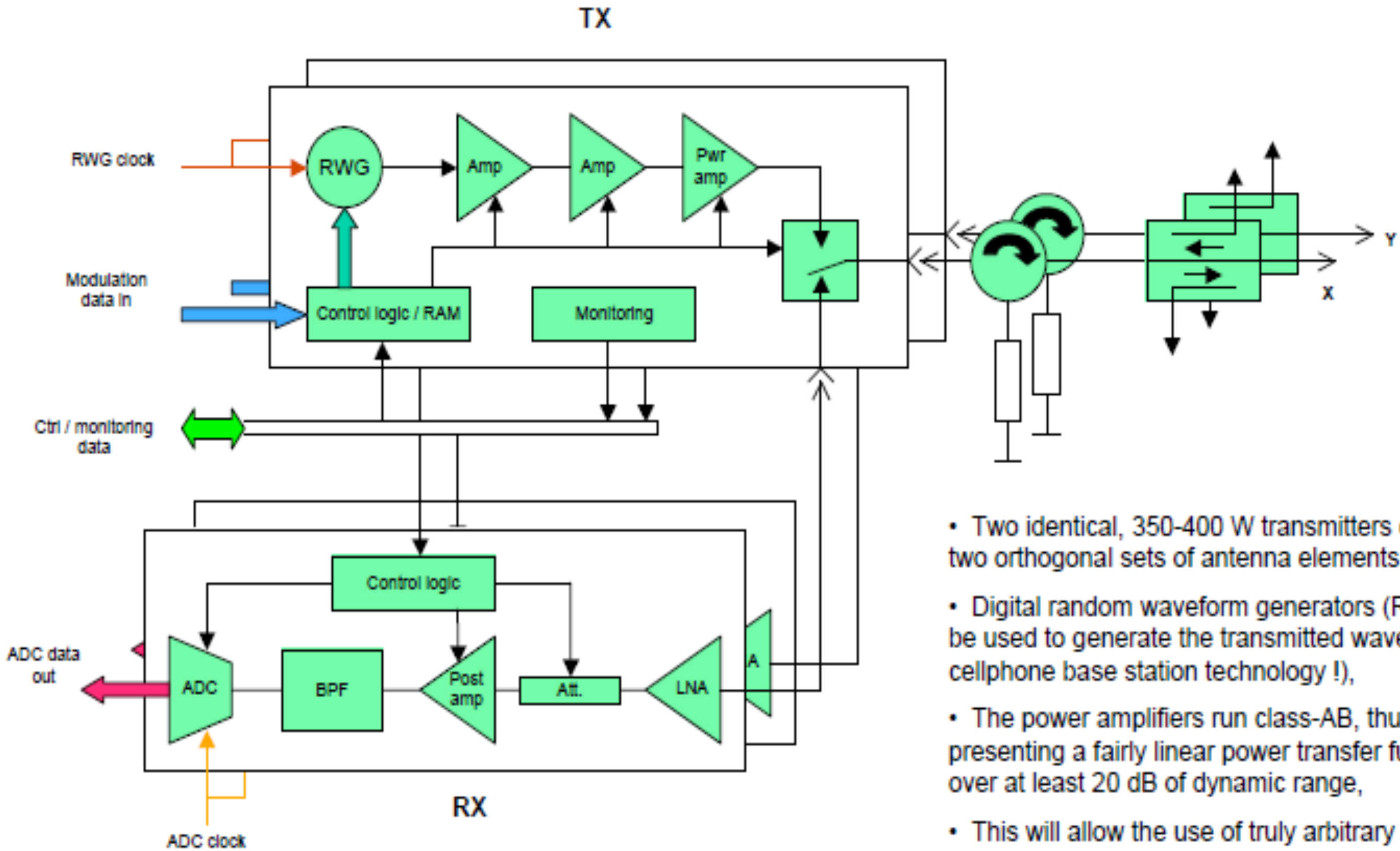




Arbitrary waveform generation

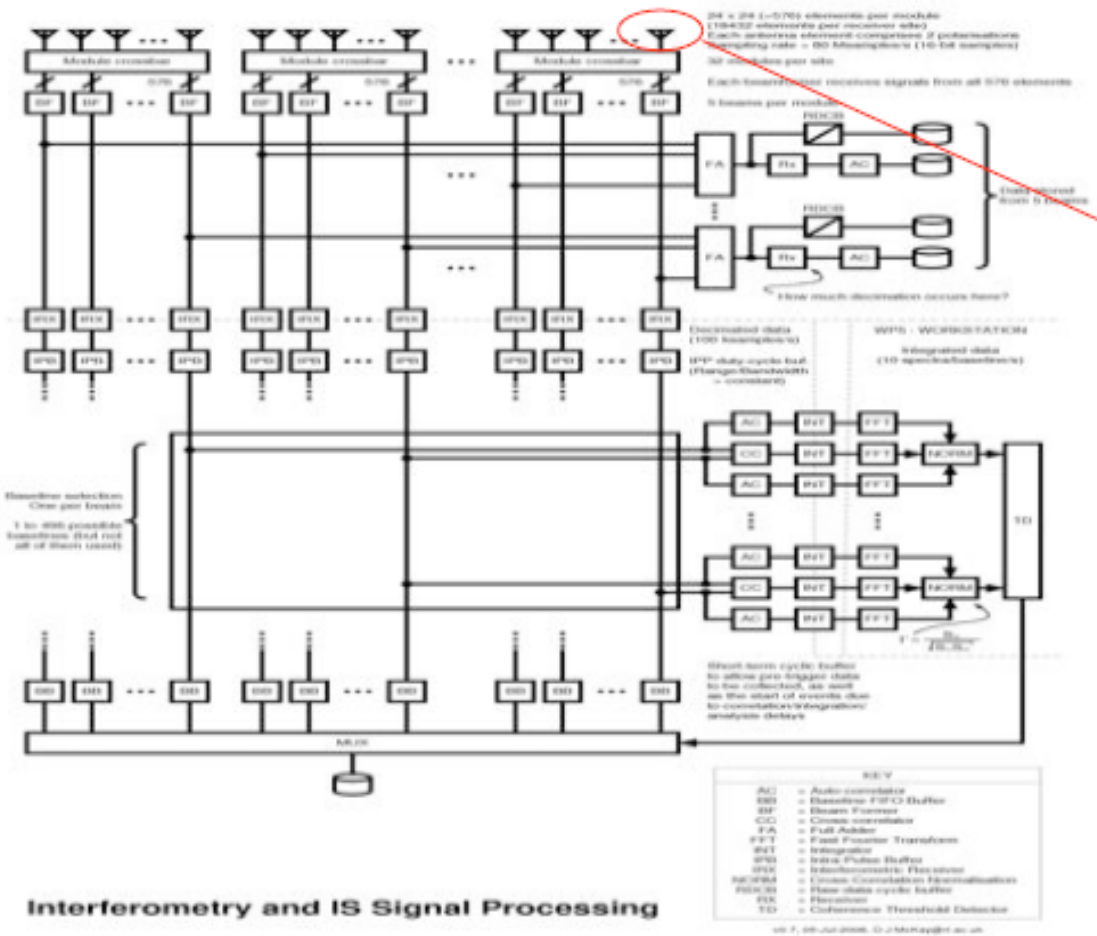
Must be rugged and mass-producible at low cost

The basic *Radio Frequency Unit (RFU)*



- Two identical, 350-400 W transmitters drive the two orthogonal sets of antenna elements,
- Digital random waveform generators (RWG) will be used to generate the transmitted waveform (cf. cellphone base station technology !),
- The power amplifiers run class-AB, thus presenting a fairly linear power transfer function over at least 20 dB of dynamic range,
- This will allow the use of truly arbitrary radar waveforms (including pseudo-noise),
- The two receiver units (one for each polarisation) are essentially the same as those used in the remote receive-only arrays, thus physically separate from the transmitter modules.

Current view of EISCAT_3D central core data flow and signal processing



Interferometry and IS Signal Processing

Front ends:

- 16 bit sampling
- 80 MHz sample rate
- 2 polarisation streams/element

⇩

- 1.28 Gb/s per polarisation
- 2.56 Gb/s per element

Array subdivided into modules:

- 24 x 24 elements/module
- 32 modules (tentatively)

18876 elements per array

⇩

Array data rate 47.19 Tb/s

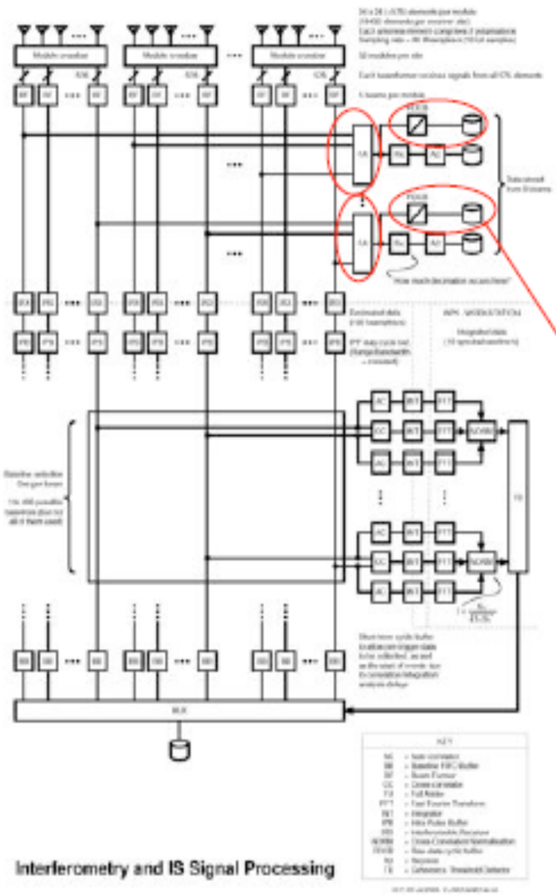
= 5.90 TB/s !!!

⇩

~ 17s on a 100 TB buffer

Storing data at this rate is obviously out of the question, the data rate must first be brought down to something in the order of the element data rate...

EISCAT_3D data types and data storage: Beam-formed data



After beam-forming, each data stream represents the sum of delayed signals from all n_{el} array elements (n_{el} = 18876 in the present case), thus bringing the data rate back to the element rate of 1.28 Gb/s/polarisation.

These are complex-amplitude data. Cannot be integrated, but could be decimated to reduce the data rate when deemed acceptable.

H, V polarisations kept separate.

Data rate/beam 2.56 Gb/s (1152 GB/H 27.6 TB/day, 10 PB/year).

Storing full bandwidth beam-formed data is still very difficult/expensive,

The standard procedure will therefore be to buffer beam-formed data for a limited time, allowing users to down-load interesting intervals to their own storage.

Assuming a receiver duty factor of 80%, a MarkVb-compliant Conduant unit will cope with the data rate from a single beam and provide about six hours of ring buffer capacity!

A possible COTS-based solution to the ring buffer problem:

Conduant MarkVa/MarkVb VLBI Data Recorder

-developed by the VLBI group at Haystack, in conjunction with a commercial firm (Conduant) that sells these systems commercially: http://www.conduant.com/products/mark5vlbi.html

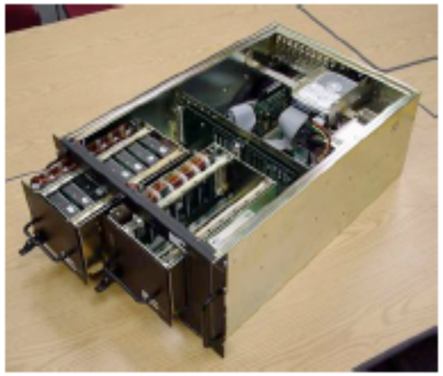
-19" rack mounted unit, comprising a PC with 2 "diskpacks" each containing 8 off-the-shelf hard drives. Each diskpack is 3.2 TB with (very approx.) dimensions of 15x25x40cm

- The software will auto-swap the disk packs as they fill up. When not being used, the "other" disk pack may be hot-swapped, thus, with supervision, the MarkVa can sustain continuous operation.

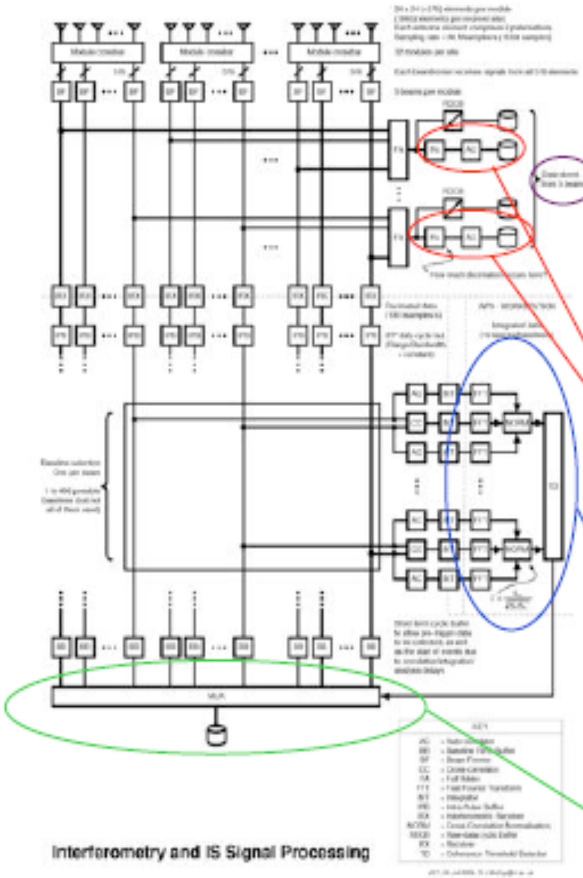
- Each MarkVa can record at 1 Gbit/s. MarkVb → 2 Gbit/s !

- The EVN has been using MarkVa systems for about 1 year with no problems.

- Haystack provide VLBI technical support for the system, see http://web.haystack.mit.edu/mark5/ for details.



More 3D Data Products:



Interferometry and IS Signal Processing

Correlated data

The first "permanent" data product:

Polarisations combined for max SNR,

Sample matrix inflated into lag profiles,

Time-windowing applied at remotes to match signal reception phase of each IPP,

Time integration applied to further reduce data vector size,

Data volumes manageable; e.g., 150 gates per profile @ 50 lags/gate generates about 150-200 MB/hour/beam.

Analysed data

A representative analysed data set will always be generated and stored

Each beam analysed separately

Standard pre-integration

Standard, well documented analysis procedure (GUISDAP),

Well defined analysis strategy

Long term storage (archive)

Volumes about n times now (since n simultaneous beams)

File-based data (easy to access particular dates/experiments)

Relational tables (easier event identification and searching).

Interferometry data

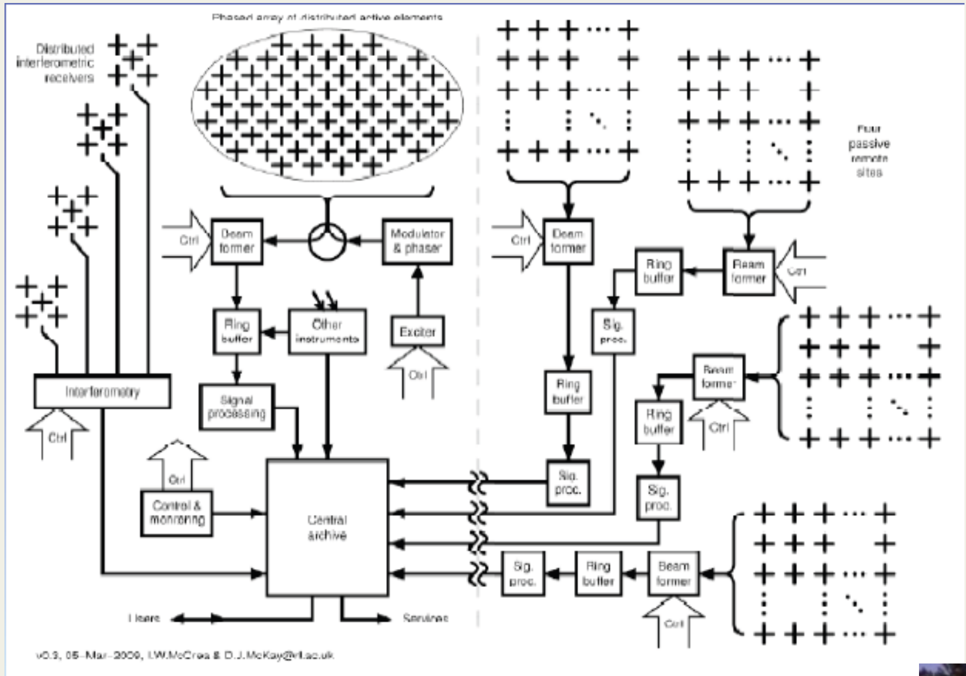
10-15 baseline pairs used in coherence detection,

Threshold logic monitors coherence levels and signals the storage system when predefined thresholds are exceeded,

Beam-formed data from each array module used as an interferometer baseline endpoint (decimated to ion line BW) are then written to short-term (ring-buffer) storage,

Interferometry users are automatically alerted and asked to copy the data to their own storage.

Most data products available in near-real time via the Web!



Design Study Results

- Full specification of high-level system
- Low-level design of many system elements
- Prototypes of antennas, signal processing
- Data system design
- Imaging system demo at Jicamarca
- Working demonstrator array
- Frequency permission for Norway
- Surveys of several possible sites

EISCAT_3D Design Study finished 30.4.2009

5 partners, 30 man years

- EISCAT, University of Tromsø, Luleå University of Technology, Rutherford Appleton Laboratory, Swedish Institute of Space Physics

Total budgeted volume 2.8 MEUR

EU FP6 support 2 MEUR

WP1: Project Management
WP2: Evaluation of design performance goals
WP3: Evaluation of options for the active element
WP4: Phased array receivers
WP5: Interferometric receivers
WP6: Active element
WP7: Distributed control and monitoring and Observation scheme
WP8: Data Archiving and Distribution
WP9: Signal Processing
WP10: New uses
WP11: Implementation Blueprint
WP12: Time and frequency distribution
WP13: Enabling procedures

The ESFRI Roadmap

ESFRI – European Strategy Forum on Research Infrastructures

Provides a roadmap for future "big" science facilities in the European research area

Not an EU process, but adopted by the European Commission in practice

44 facilities on current roadmap

Sweden proposed EISCAT_3D to roadmap

Accepted December 2008 as an environmental facility

Having ESFRI status opens many doors....

FP7 Preparatory Phase

Application submitted December 4 2009

14 work packages:

WP1: Management and reporting
WP2: Legal and logistical issues
WP3: Science planning
WP4: Outreach activities
WP5: Consortium building
WP6: Performance specification
WP7: Signal processing
WP8: Antenna, front end and timing
WP9: Transmitter development
WP10: Aperture synthesis imaging
WP11: Software theory & implementation
WP12: System control
WP13: Data handling & distribution
WP14: Mass-production & reliability

TOTAL: 5.[illegible]M Euros

EISCAT_3D

A European Three-Dimensional Imaging Radar for Atmospheric and Geospace Research

Application for Preparatory Phase Funding under the European 7th Framework

Why do we need a Preparatory Phase?

Objectives:

- **to provide catalytic and leveraging support for the preparatory phase leading to the construction of new RIs**

- **Building primarily upon the work conducted by ESFRI**
- **Bringing the project to the level of legal and financial maturity**
- **Involving all the necessary stakeholders to make the project move forward, take decision, etc.**
- **Activities: legal work, governance, strategic work, financial work and, if necessary, technical work**
- ***Funding scheme: CP-CSA (combination of 'collaborative project' & 'coordination and support actions')***

Strategic Work

We need:

- new partners
- publicity
- development of science case
- new communities to broaden science base
- frequency permissions
- discussions with governments, local communities...
- sites and building permissions
- provision of infrastructure
- manufacturers to build the system

Financial Work

We need:

- to fully quantify the commitment needed
- build a financing consortium
- make a cost model for construction and operations
- decide how best to use the money we have

Technical Work

We need:

- Continually revision and updating of the PSD
- Design of the signal processing system
- Develop system software (DSP, coding, analysis, control)
- Evaluate all antenna options, test prototypes
- Develop front end and timing system
- Prototype the transmitter
- Optimise the imaging system
- Review data system implementation
- Discuss mass production and quality control issues

Relationship to the Design Study

Design study ran four years 2005-2009

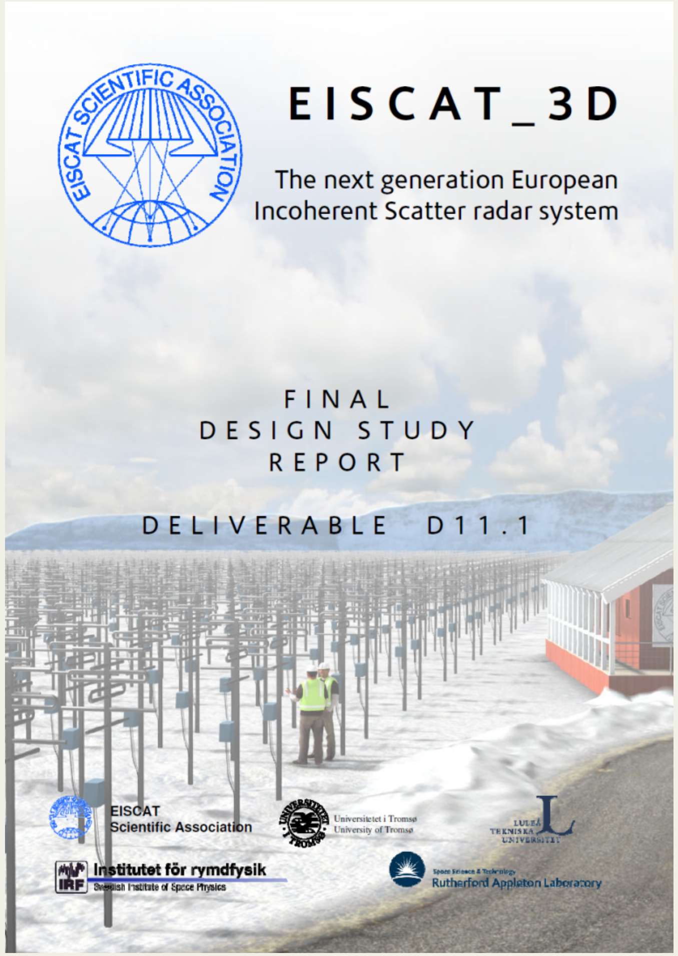
Excellent groundwork for many areas:

- Performance Specification
- Site surveys
- Frequency allocations
- Science Case
- Antennas
- Front End
- Beam-forming
- Imaging systems
- Transmitter
- Data system

One large area unclosed:

- Signal processing

Looking at other options in FP7 does not mean rejecting the design study !!



FP7 Application

Submitted December 3rd 2009

Total Value EUR 5.9M

8 project partners:

EISCAT Scientific Association
University of Oulu
Lulea Technical University
University of Tromso
Swedish Institute of Space Physics
Swedish National Infrastructure for Computing
STFC Rutherford Appleton Laboratory
National Instruments (Belgium)
Swedish Research Council (VR)

EISCAT_3D

A European Three-Dimensional Imaging Radar for Atmospheric and Geospace Research

Application for Preparatory Phase Funding
under the European 7th Framework

Roles of the Project Partners

- EISCAT: Project management and reporting, site selection, consortium building, performance specification, system control, mass production issues, outreach activities
- University of Oulu: Signal processing, software development, theory, science planning
- University of Luleå: Antenna, front end and timing synchronisation, mass production issues
- IRF Kiruna: Transmitter development
- University of Tromsø: Radar imaging, site selection
- STFC RAL: Science planning, performance specification, project management
- National Instruments: Signal processing and timing, mass production issues
- VR-SNIC: Data handling and distribution

Overall Staff and Resources

	EIS	UIT	LTU	IRF	STFC	VR	VR/SNIC	UOULU	NI	tot	
WP1	18	0.8	0.8	0.8	9	0.8		0.8	0.8	31.8	
WP2	17	6								23	
WP3					11			16		27	
WP4	24									24	
WP5	22	6				4				32	
WP6	4				2			28		34	
WP7	34							12	10	56	
WP8			48						2	50	
WP9				30						30	
WP10		24								24	
WP11								45		45	
WP12	15									15	
WP13							24			24	
WP14	12		10						6	28	
tot	146	36.8	58.8	30.8	22	4.8	24	101.8	18.8		443.8
										443.8	

Preparatory Phase Discussions

- Evaluation received March 2010
- Passed threshold, selected for funding
- First negotiation meeting, April 9th
- Agreed funding of 4.5M Euro
- Revised plan submitted end of May
- Contract signed by EISCAT, waiting signature from Commission
- Preparatory Phase should start 1st October
- Kick-off meeting, October 20-21, Stockholm
- Some national funding awarded (e.g. for LOFAR development) some under review

Norwegian government published 12.3.2009 their development programme for Northern Areas

LOFAR hardware for EISCAT_3D

18 Core station fields

- 96 Low Band Antennas
- 2 x 24 High Band Antenna Tiles (HBA field is split)

18 Remote station fields

- 96 Low Band Antennas
- 48 High Band Antenna Tiles
- Microbaromater (infrasound)

10 Geo-Remote station fields

- Geophones
- Microbarometers
-

8 International station fields

- 96 Low Band Antennas
- 96 High Band Antenna Tiles

Getting Involved

- Several opportunities for working groups etc during the PP project
- Become an "associate partner" of EISCAT_3D
- Energise your national community to be part of it
- EISCAT_3D is for everyone, not just EISCAT members
- Uppsala Users Meeting: May 19-21 2010

Contact us!!!

ian.mccrea@stfc.ac.uk

esa.turunen@eiscat.se

http://www.eiscat3d.se/


Unique science opportunity in order to answer important fundamental questions:
- How does solar variability affect the atmosphere in the Arctic and how do the atmospheric regions couple to each other?
- What is the intrinsic nature, behavior and role of turbulence in the neutral atmosphere and space plasmas?
- What is the role of dust and aerosols in upper atmosphere and lower ionosphere and how does the meteoric input affect the whole atmosphere?
- What are the mechanisms, variability and significance for global atmospheric evolution of ion outflow at high latitudes?
EISCAT_3D + EISCAT Svalbard Radar
+existing infrastructure (Andoya, Esrange,SIOS, Heating, Radar, Lidar, Riometer, Magnetometer, GPS, Tomography receivers, etc.)
European
Window to Geospace in Northern Scandinavian Arctic

EISCAT_3D Digital Receiver Front End: Performance Requirements and Design Concepts

Assumptions:

- Bipolar 2s complement ADC with full-scale voltage = ± 0.5 volt
- 12 bits (b0 - b11)
- 50+j0 ohm input impedance
- Noise floor established by amplified sky/antenna/preamp noise
- Gaussian white noise
- RMS noise voltage, U_N at the 3-bit level
- Very low SNR
- Equivalent noise BW = 10 MHz

Quick-and-dirty estimate of required front-end gain:

- Voltage per ADC bit:

  $U_b(i) = 0.5 \cdot 2^{(i-10)}$

- Set the front-end power gain G such that $|U_N|$ equals b2:

  $U_N = (G \cdot (4\,k\,T\,B\,R_L))^{0.5} = 0.5 \cdot 2^{(2-10)} = 1.953\ \exp(-3)$ V

- Known quantities:

  $k = 1.38\ 10^{-23}$

  $T = 150$ K

  $B = 10^7$ Hz

  $R_L = 50$ ohm

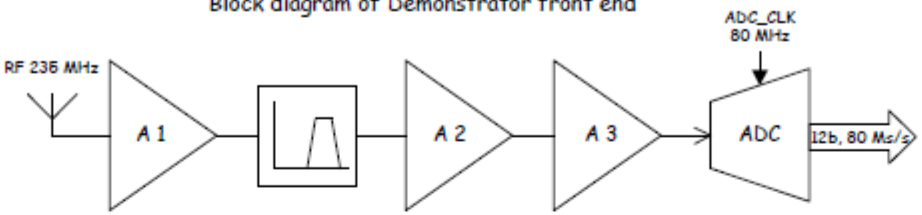
$|4\,k\,T\,B\,R_L| = 1.035\ \exp(-12)$;

$G = U_N^2\ /\ |4\,k\,T\,B\,R_L| = 65.7$ dB

The 3D receiver front end is a key element in the project:

- Digital beam-steering and multi-beaming requires that the data from every element antenna is available in digital format, i.e. every antenna must have an ADC fitted,
- To reduce the front-end component count, straight amplification followed by constructive under-sampling will be employed (sampling clock running at ~ 80 MHz, signal at ~ 235 MHz in 6th Nyqvist zone),
- Large bandwidth (> 15 %) low-noise performance at VHF requires unusual design choices in first amplifier stage (X band medium power GaAsFET...)
- Because of the presence of the remote sites, the total number of receivers is more than twice the number of active elements (> 30000) ; therefore a common front end design will be developed and used throughout the system,
- It is planned to eventually develop fully integrated front end systems on silicon,
- This slide illustrates the proof-of-concept work currently going on in connection with the Demonstrator array; a total of 24 front ends of a similar design being built.

Block diagram of Demonstrator front end



A 1:	MGF1801	G = 21 dB, Tn = 25 K
A 2, A3:	MGA62563	G = 23 dB, Tn = 60 K
FL1:	BPF	G = -2 dB, BW = 10 - 30 MHz

$G_{tot} = 65$ dB, $T_{n,\ tot} = 26$ K

Science Case Structure

- Executive Summary
- Key Capabilities (of EISCAT_3D)
- Section A: Science Topics
  - Atmospheric Coupling
  - Space Plasma Physics
  - Small-scale structure
  - Large-scale processes
  - The Geospace Environment

[redacted]

- Section B: Technique development
  - Volumetric Imaging
  - Aperture Synthesis Imaging
  - Tracking/adaptive experiments
  - New techniques (coding, analysis, applications)
- Section C: Service applications
  - Modelling, space weather
- Section D: Feedback into radar design

[redacted]

- The set of science topics is intended to be all-encompassing.......
- .....but the listed choice is perhaps somewhat arbitrary...
- There is plenty of overlap between headings
- The list of science topics:
  – Should not be too long
  – Should be understandable to any educated person
  – Should highlight issues they regard as relevant

Summary

- Lots of compelling science to be done
- But we must:
  - Define the programe properly
  - Collaborate internationally
  - Use the experience of the whole community
  - Co-ordinate closely with the PP study
  - Present it in the best way possible
  - Ensure that people “buy in” to our vision

- WP3 talk on Friday discusses how we go forward

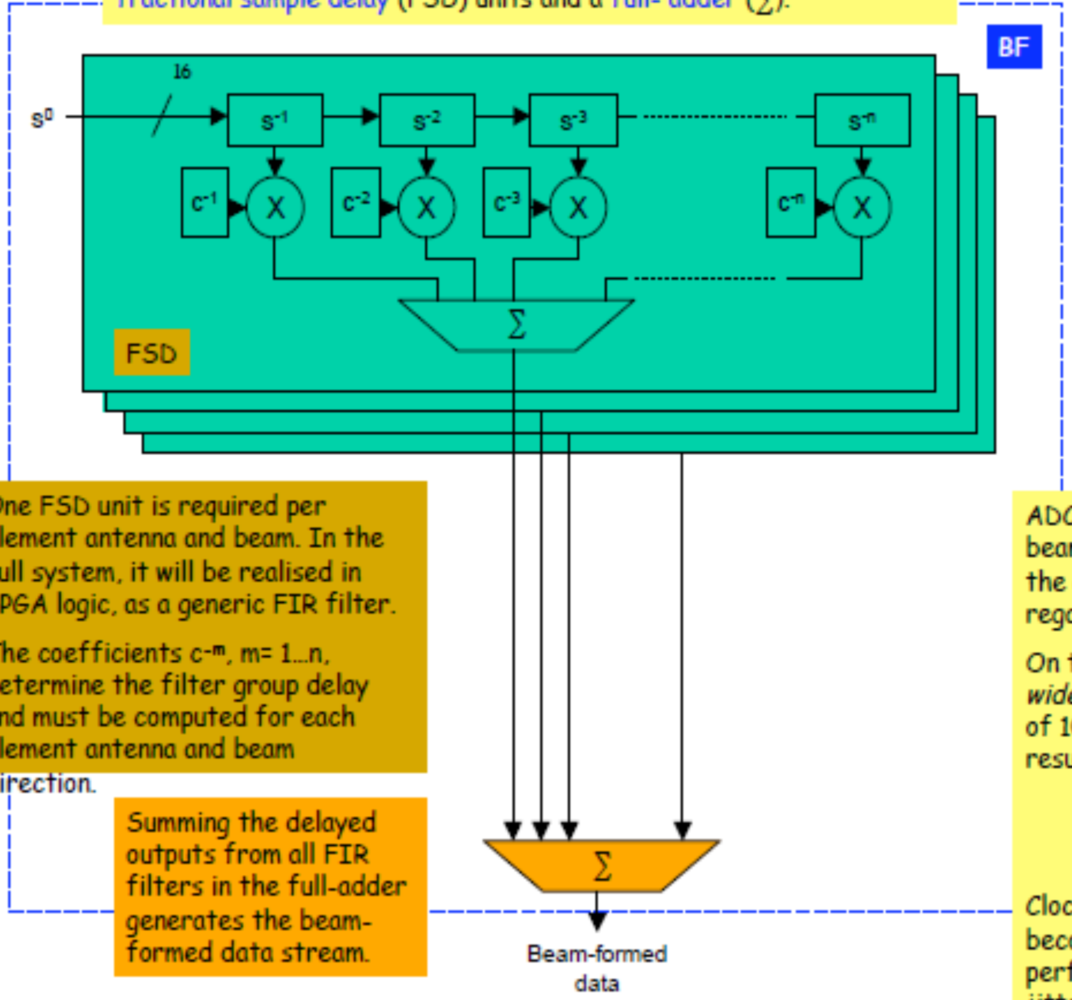
Feedback to radar design

Specifications for auroral studies

- Up to 500 km
- Spatial resolution: 10 meters
- Temporal resolution: 0.05 seconds
- Simultaneous measurements on "all" scales

Digital beam-forming: beam-forming logic, multi-beaming and beam errors

A digital beam-former (BF) consists of two main parts, viz. a set of fractional sample delay (FSD) units and a full- adder (∑).



One FSD unit is required per element antenna and beam. In the full system, it will be realised in FPGA logic, as a generic FIR filter.

The coefficients c^{-m}, m= 1…n, determine the filter group delay and must be computed for each element antenna and beam direction.

Summing the delayed outputs from all FIR filters in the full-adder generates the beam-formed data stream.

Multiple beams can be generated from the same data by simply adding more beam-formers, one per beam!

ADC timing jitter and other timing errors affect the beam, but when the error distribution is Gaussian, the average pointing direction stays the same regardless of the width of the distribution.

On the other hand, *Gaussian timing jitter causes a widening of the beam and a loss of gain.* A 3-σ jitter of 100 ps results in a 0.1 dB gain loss; 500 ps jitter results in almost 2 dB gain loss !

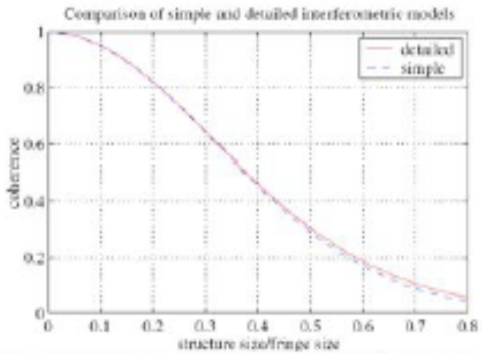
Clock distribution and ADC sampling stabilisation now become important issues; in order not to lose performance, the system is being designed for a 3-σ jitter of less than 100 ps, array-wide.

3D Interferometry requirements - consequences for the core array design

(data courtesy of Tom Grydeland/Cesar la Hoz, UiT)

Requirements regarding baselines

The longest baselines



The longest baselines

- Needed to resolve fine structures
- Finest structures expected to match structure in visible aurora
- Target resolution: 20 m at 100 km
- $\theta = 2 \cdot 10^{-4}$
- To achieve coherence of 0.6, need baseline of 750λ
- At 225 MHz, this is about 1000 m
- If the main array is smaller than this, consider "outlier" modules
- For 20 m at 100 km, $\rho = 0.8$, $\Rightarrow 1000\lambda$

To form the longest baselines, 3 or more outlier, RX-only modules will be deployed at up to 1500 m from the array midpoint.

Requirements regarding baselines

Total number of baselines

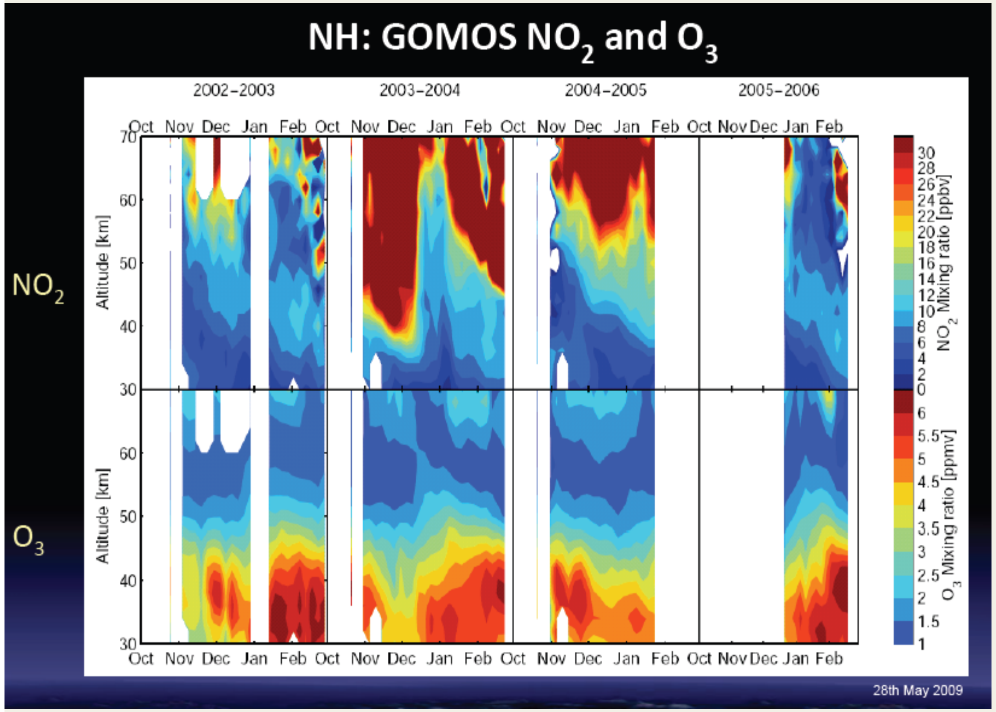
- Visibility samples at all scales: 6, 15, 30, 60, 150, 300 and 750λ
- Suggests ~ 20 modules for full 2D imaging capability
- A total of ~ 150 baselines
- Smaller initial configuration will also be useful

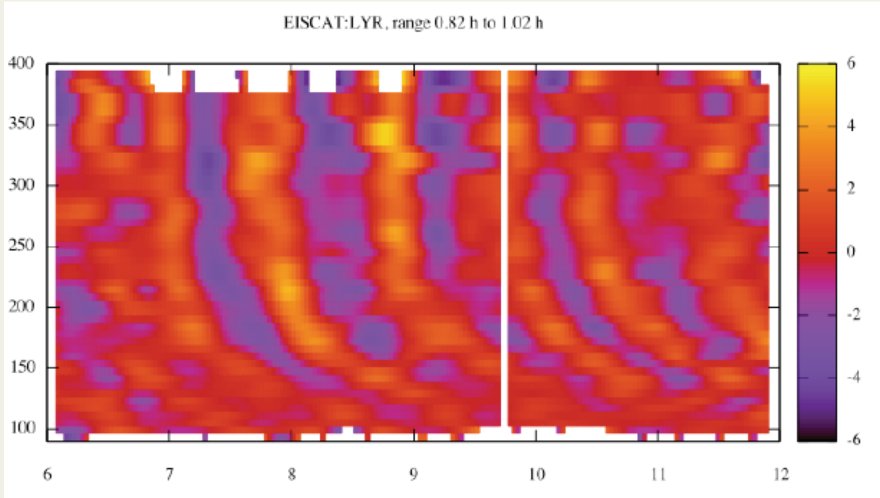
This suggests that the main array can usefully be organised hierarchically, with elements grouped together in small groups of diameter = 6 λ (7.5 m).

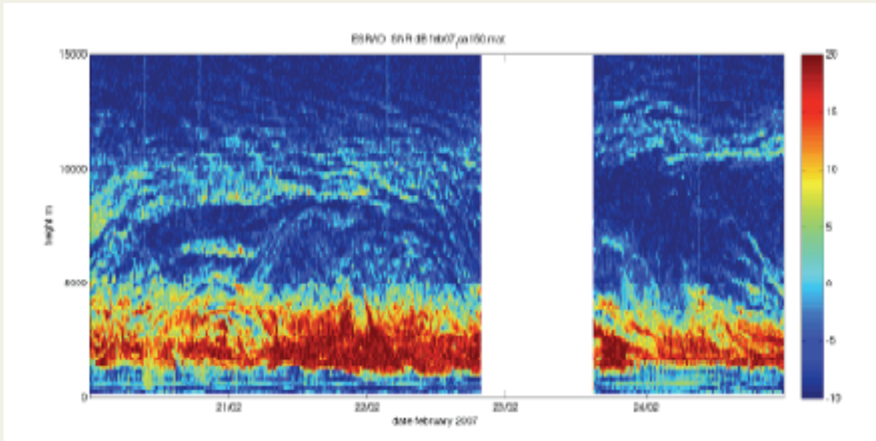
The main aperture diameter should be at least 150 λ (188 m) to enable these baselines to be constructed internal to the aperture.

This accommodates 25 or more 6λ-modules and matches the aperture size required for target IS performance very well indeed !

Atmospheric Coupling: Dynamics







Feedback to radar design

	Coherent Echo resolutions			Incoherent Scatter resolutions		
Region	Height	time	horiz	Height	time	Horiz*
85 km	< 100m	100ms	30m	1 km	1-10s	1 km
110 km	100m	10 ms	100m	1 km	1s	10m*
250 km	100m	10 ms	100m	1-2 km	1s	10m*

Mike Rietveld, Thomas Leyser

3D Demonstrator array 2007-07-16:

- All 48 Yagi antennas now in place,
- Row-level (4:1) power-combiners installed and cabled.

The blue dot ●

indicates one of the row feedpoints.

Operation of all 24 feeds verified by network analyser; s_{11} typically ≤ -26 dB over (222 - 226) MHz