**ESWW9 / PROBA2 splinter**

# Impact of Solar X-ray Flares on the Earth lower ionosphere

## relating LYRA – GOES - VLF data

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**JOINT WORKING GROUP**

**OBSERVATIONS**

In Space:

# OUTLINE

**Observe and measure Flares!**


GOES


LYRA?

SOHO

- Observations of the effects of Solar X-ray flares from Earth – VLF transmission
- How we correlate with space based measurements – GOES
- How we model: N(t,h), LWPM
- Can we exploit LYRA data?
- Results
- Summary


SDO

# OBSERVATIONS:

On Earth:

D-region

**VLF**
**$f < 30$ kHz**

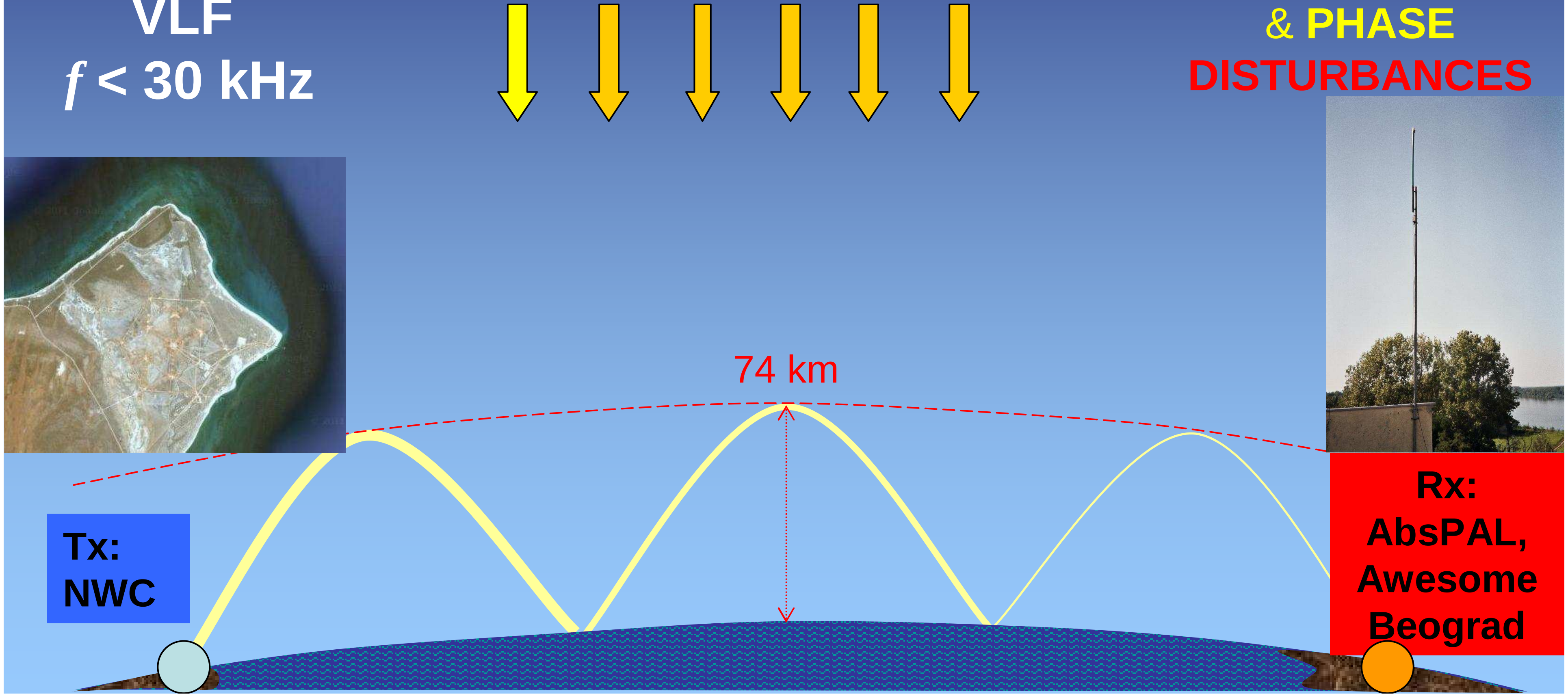
**Radiowave propagation**

(Supported by NOSC **LWPC)**

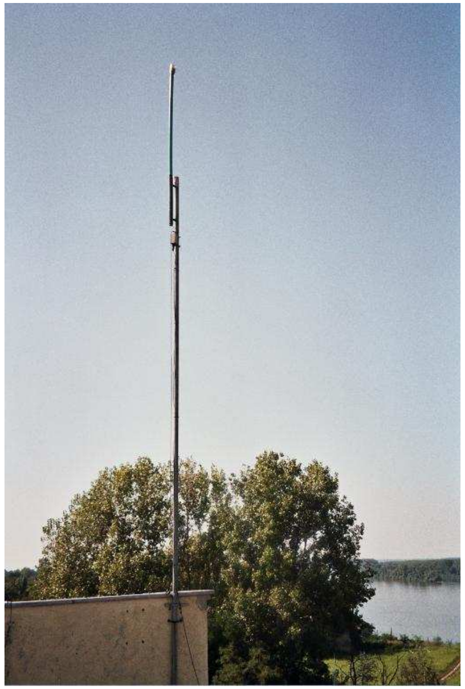
Solar Lyman Alpha (121.6 nm)

during flares: **Solar X-rays**

measure
**AMPLITUDE**
& **PHASE**
**DISTURBANCES**



# Radiowave propagation



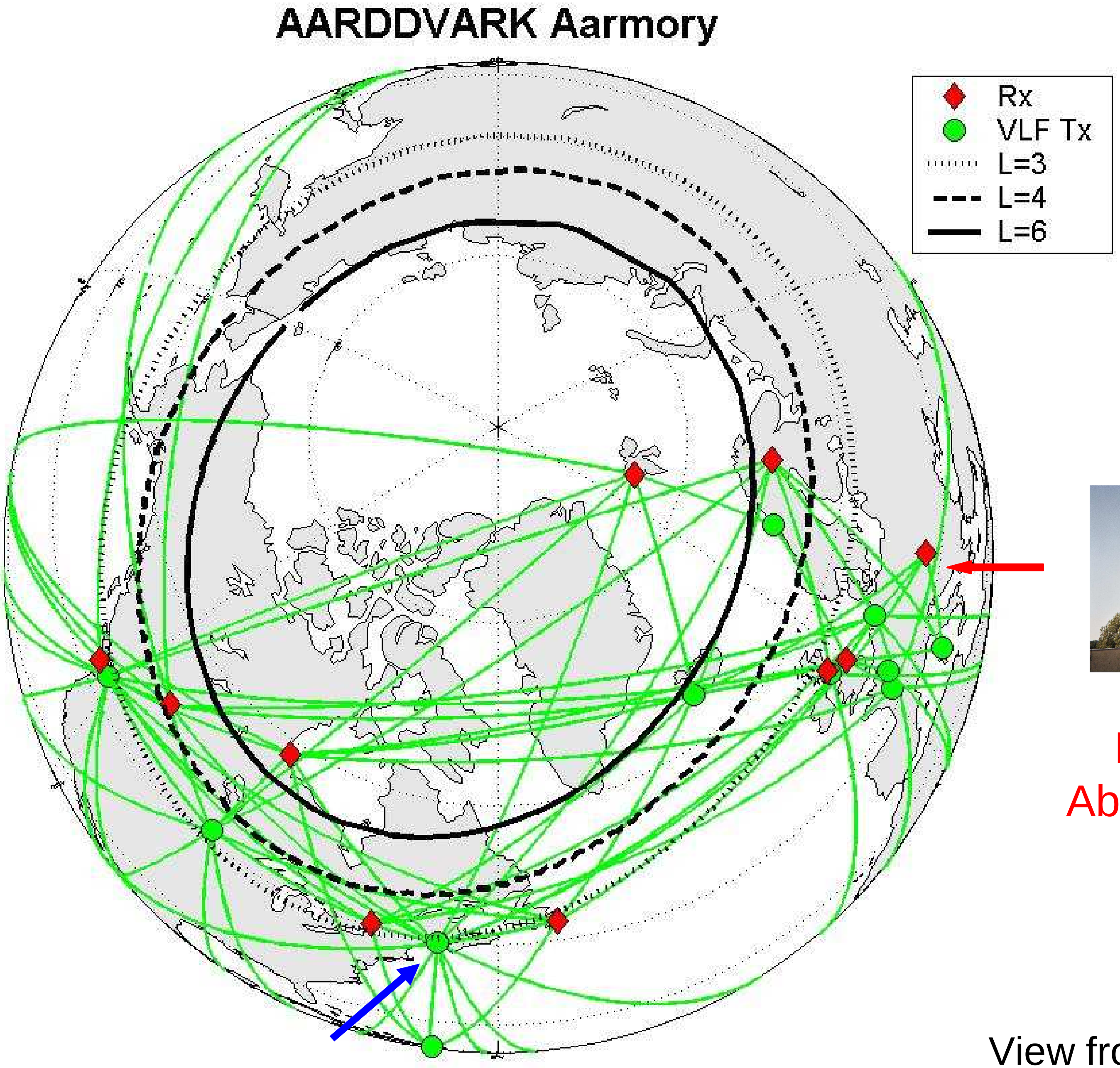
**RECEIVERs Rx:**
**Beograd**
(44.85 N; 20.38 E)

**AbsPAL**

**AWESOME**

**TRANSMITTER Tx:**
**Harold E. Holt**
**North West Cape**
**NWC** (21.S ;114.2 E)

Antarctic-
Arctic
Radiation-belt
Dynamic)
Deposition –
VLF
Atmospheric
Research
Konsortia

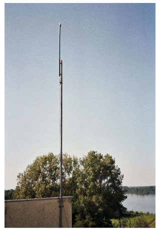


NAA/24.0 kHz

View from
Arctic

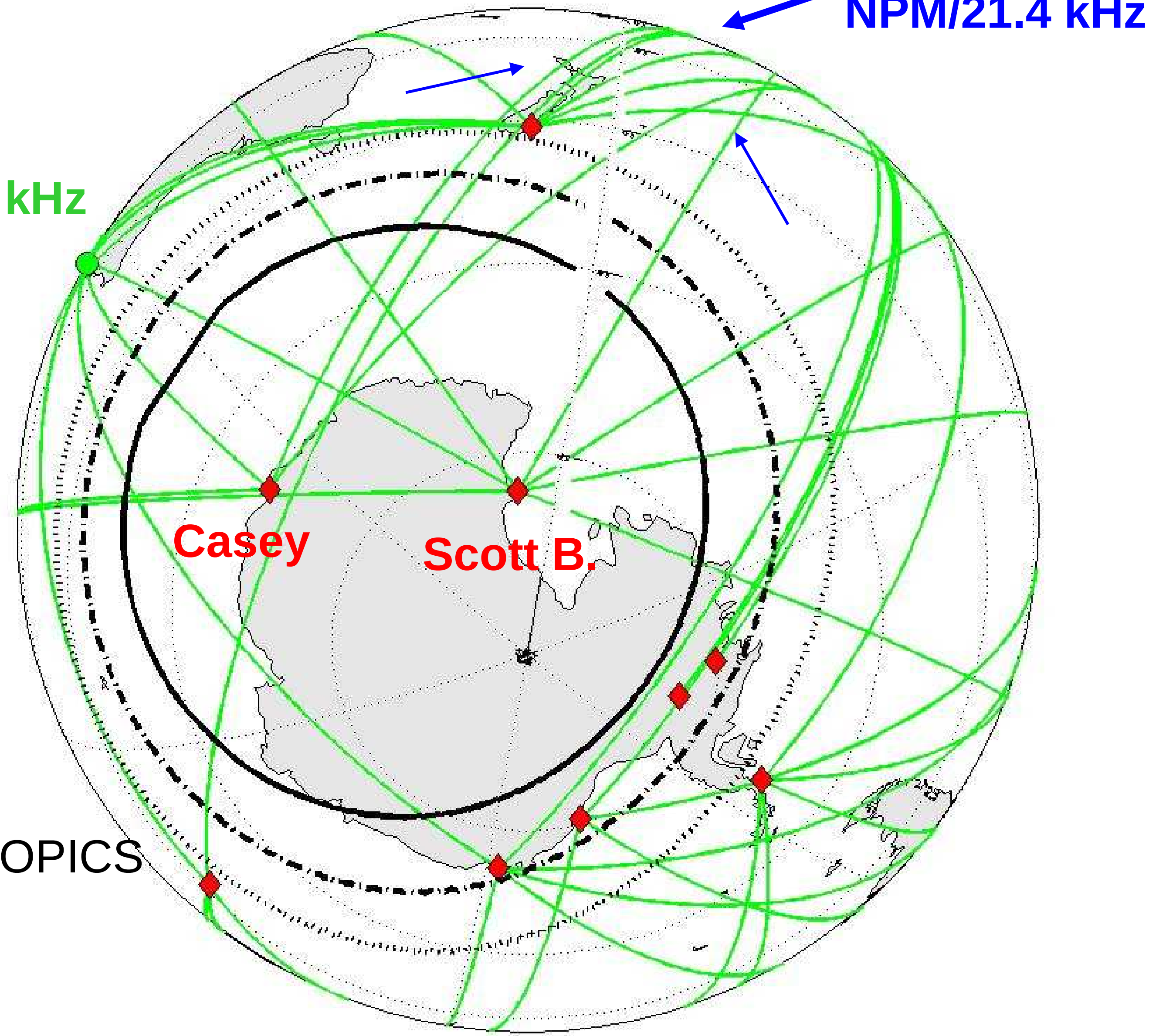
**e.g.**
**Tx::**
**NAA/24.0 kHz**:
(44.65 N; 67.3 W)
**GQD/22.1 kHz** :
(54.72 N; 02.88 W)
**ICV/20.3 kHz:**
(40.92 N;9.73W)
**NWC/19.8 kHz:**
(21.8S; 114.2 E)

**Rx:**



BG
AbsPAL

## AARDDVARK Aarmory



SCIENCE TOPICS

- SPE
- REP
- **SOLAR FLARES**

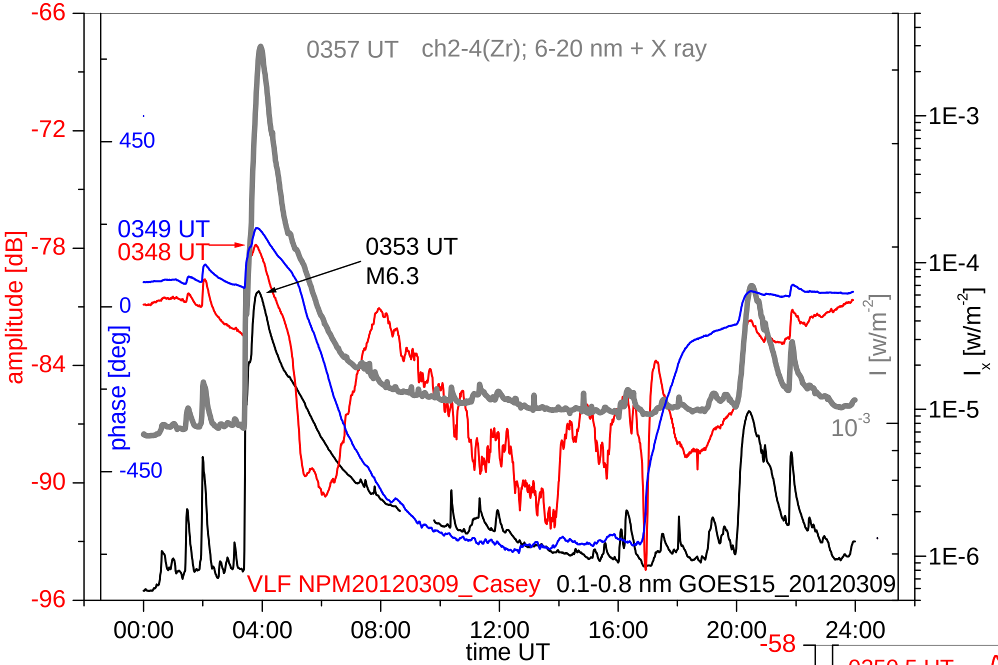
# OBSERVATIONS

## Flare – active 9March 2012

Solar Irradiance

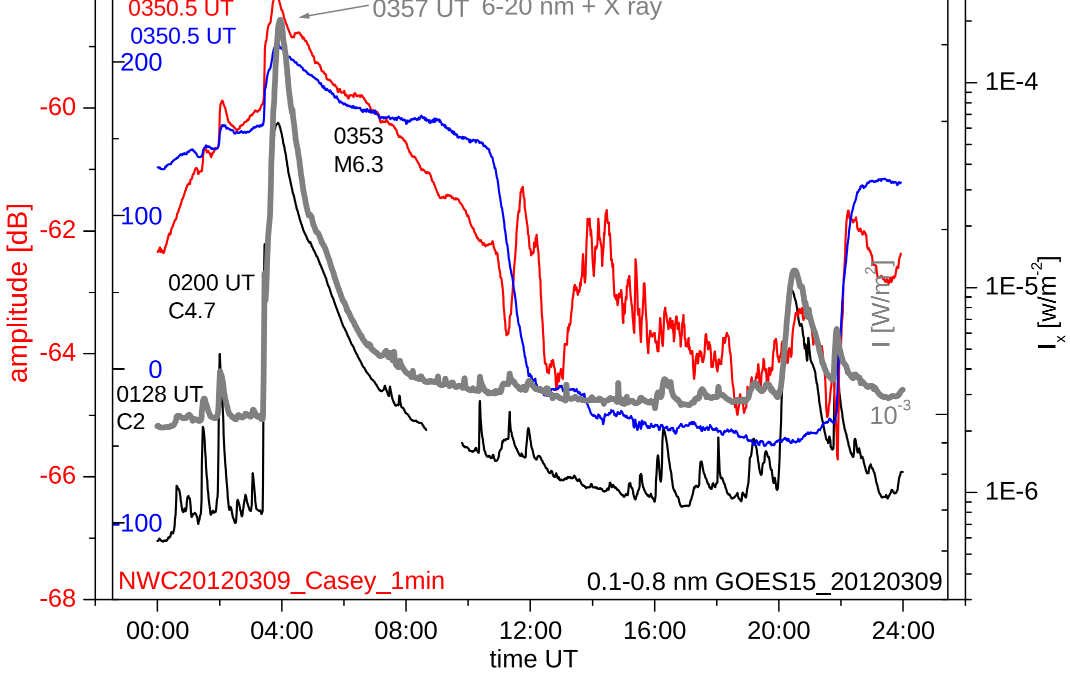
**GOES 15** **LYRA**

**NPM - Casey** : VLF Amplitude & Phase



**NPM/21.4 kHz**

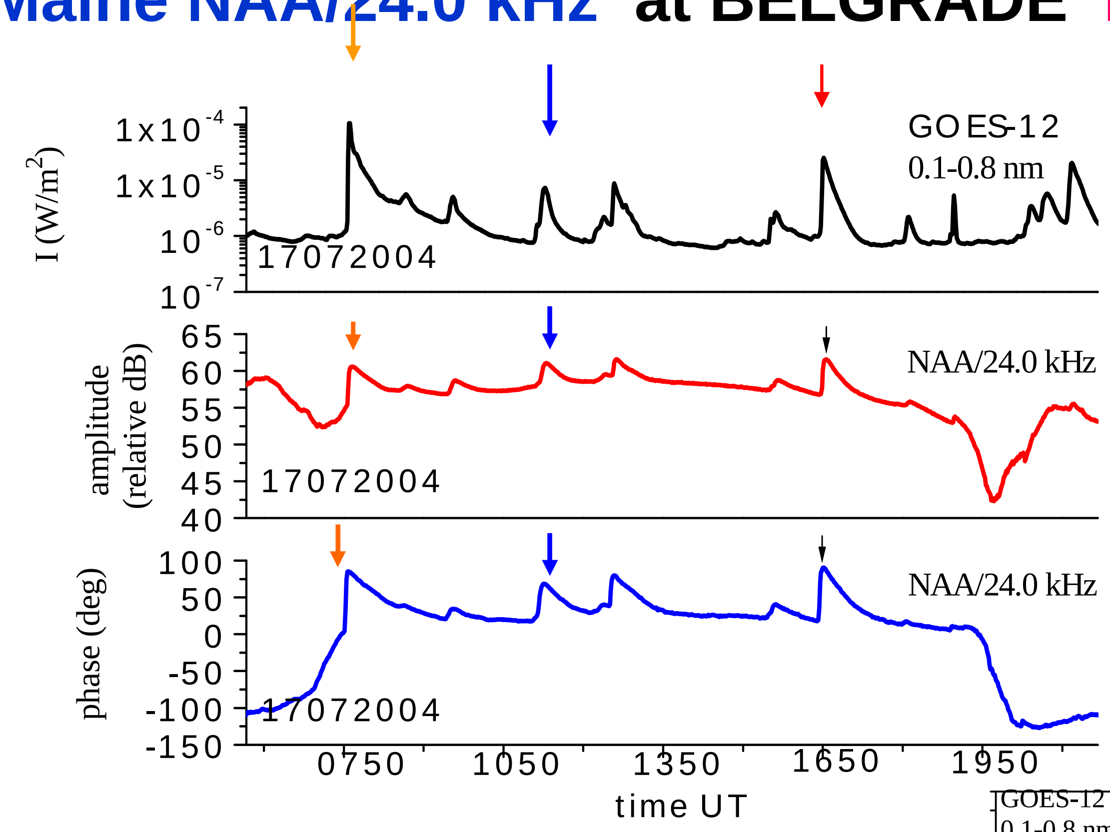
**NWC - Casey** : VLF Amplitude & Phase



**VLF**: **AMPLITUDE**
**PHASE**
**at**
**CASEY**

**NWC/19.8 kHz**

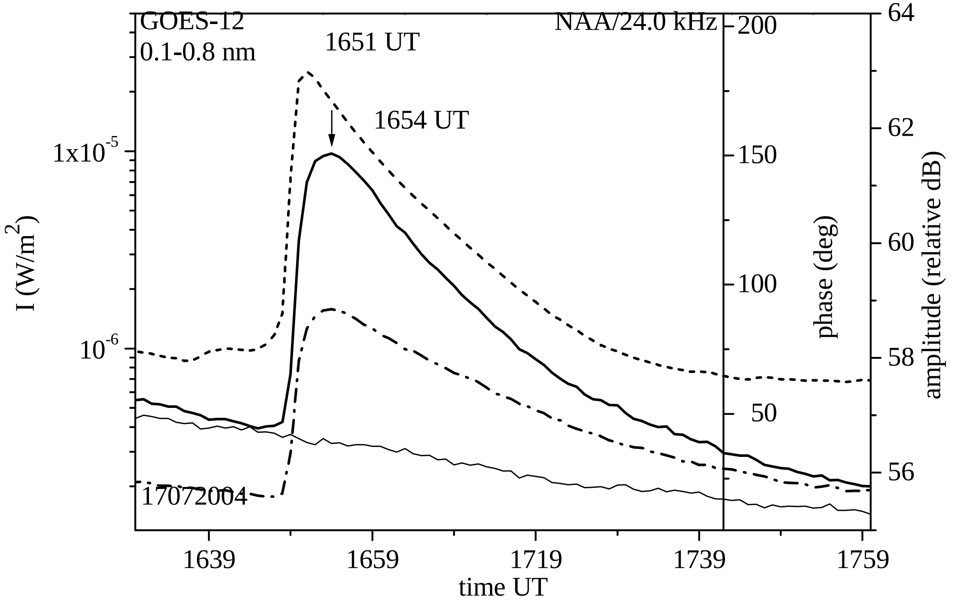
# Maine NAA/24.0 kHz at BELGRADE Flare – active 17July 2004



**X1.1** 0757 UT 110μW/m$^2$

**C7.3** 1137 UT 7.3μW/m$^2$

**M2.5** 1651 UT 25.4μW/m$^2$



C7.3

$$\Delta t = 2\,\mathrm{min}$$
$$\Delta A = 3\mathrm{dB}$$

M2.5

$$\Delta t = 3\,\mathrm{min}$$
$$\Delta A = 5\mathrm{dB}$$

# **LWPC model** Wait model of the quiet ionosphere (1970)

*For quiet ionosphere*

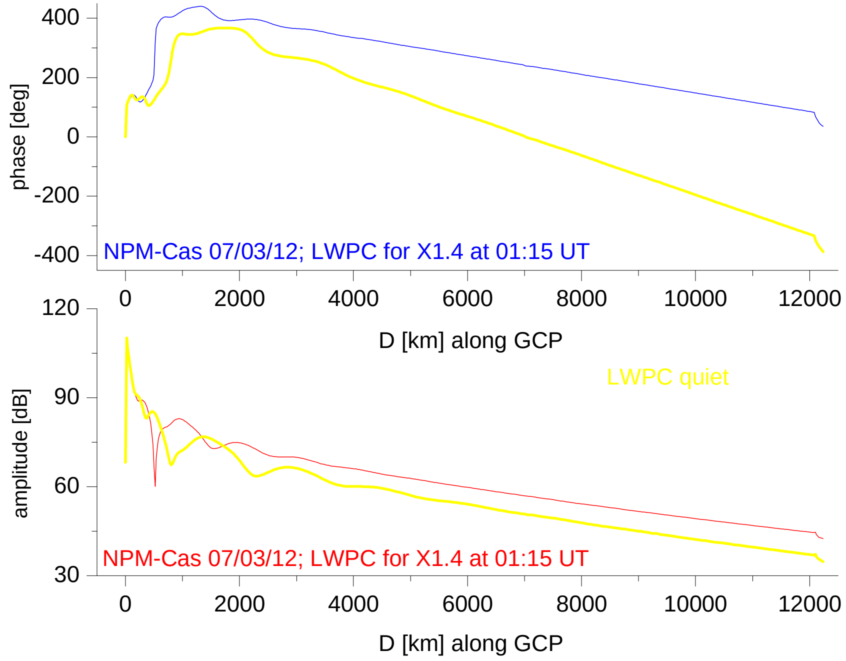
***Initial concentration N(t=0, h)***

*For solar-flare conditions:*

***N(h),***

***To validate the N(t,h) model***

$\beta$ -sharpness, ***H'*** – reflection height



NOSC: **Computer programme for the assessment of long wave Propagation**

**L**ong **W**avelength **P**ropagation **C**apability,

**Input** :

Tx and Rx coordinates

Time

Angle of magnetic inclination

Conductivity

$\boxed{\beta \quad H'}$

**Output**:

VLF amplitude and phase along the trace, from Tx to Rx

# OBSERVATIONS - MODELLING:

## KEY parameters:

MEASUREMENTS:

2004 -2007…2010...**2012**

*I(t), A(t), P(t)*

$\Delta A$ **< 0**

$\Delta A$ **> 0**

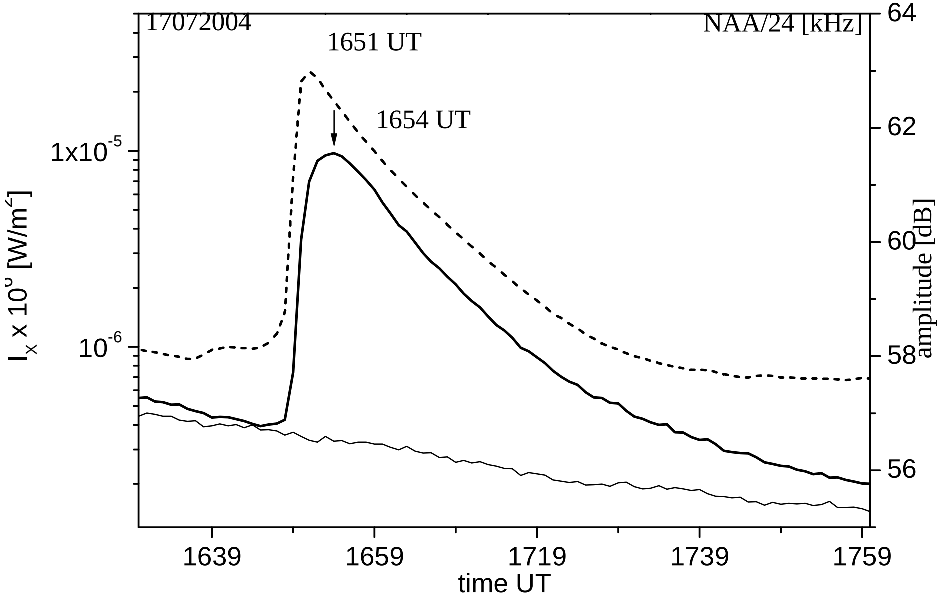
$\Delta t$ **> 0**

Time delay (*Appleton,1953,* Journal of Atm. Terrestrial Physics *JATP, 3, 282*) “slugishness”
(time shift of maximum N with respect to regular diurnal flux at $\chi$=0)

$$\Delta t = t_{A_{max}} - t_{I_{max}}$$

$$A_{max}\ ,\ I_{max}\ ,\ I(A_{max})\ ,\ A(I_{max})$$

**NAA/24.0 kHz 17July 2004, 1651 UT**



300 , **250** events

**Assumption:**

$$t_{A_{max}} \equiv t_{N_{max}}$$

$$I\ (A_{max}) \equiv I\ (N_{max})$$

# MODELLING:

Multicomponent hydrodynamics $N, N^{+}, N^{-}$ ⟶ Continuity equation elementary process kinetics

$$\frac{dN}{dt} = \frac{q}{(1+\lambda)} - \alpha N^{2} - N\frac{d\lambda}{dt}\frac{1}{(1+\lambda)}$$

time dependence!

$$\boxed{\frac{dN}{dt} = q - \alpha N^{2}}$$

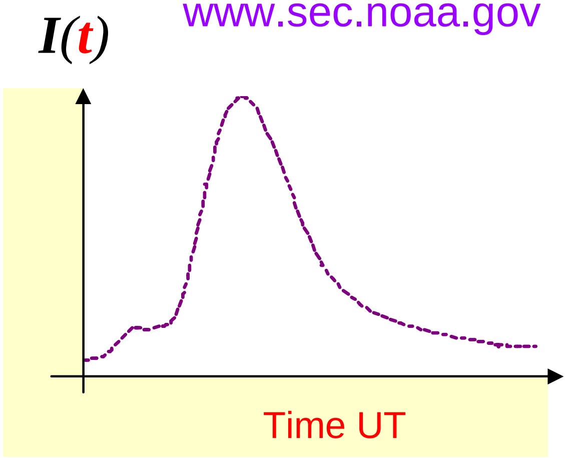
$$q = (C/eH)\, I \cos\chi$$

- $\alpha$ - effective electron recombination coefficient
- $q$ - rate of electron production
- $C$ – number of electrons per unit of energy
- $H$ - scale height
- $\chi$ – solar zenith angle
- $e$ – base of natural logarithm

$$q(t) = k\, I(t)$$

$$k \equiv \frac{C}{eH}\cos\chi$$

from NOAA www.sec.noaa.gov



**Why not LYRA?**

From LWPC or IRI:
preflare $N(t=0)$

$$\boxed{k, \alpha ?}$$

# Time delay, but for the active ionosphere:

$$N(I_{\max}) = \frac{1}{2\alpha\,\Delta t} \longrightarrow \boxed{N_{\max} = N_{\max}(\Delta t, k, \alpha, I_{\max})} \quad (1)$$

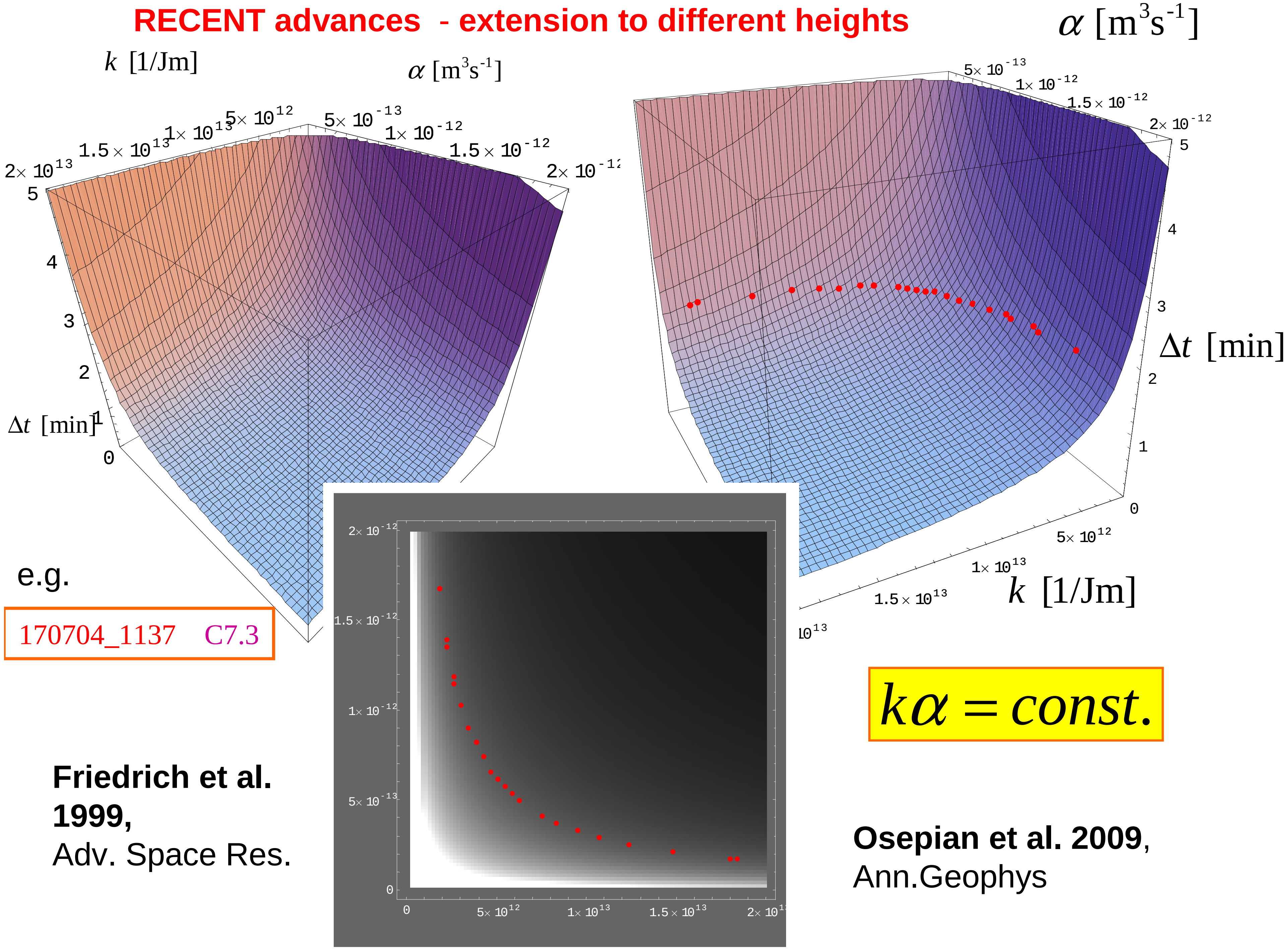
$$\frac{dN}{dt} = q - \alpha N^2 \longrightarrow \boxed{(N_{\max})_{DE} = \sqrt{\frac{kI(N_{\max})}{\alpha}}} \quad (2)$$

Agreement of (1) i (2) yields:

$$\boxed{k\alpha = const.}$$

$$\mathbf{q}(t) = \mathbf{k}\,\boldsymbol{I}\,(t), \qquad k \equiv \frac{C}{eH}\cos\chi$$

# RECENT advances - extension to different heights



e.g.

170704_1137 C7.3

$$k\alpha = const.$$

**Friedrich et al. 1999,**
Adv. Space Res.

**Osepian et al. 2009**,
Ann.Geophys

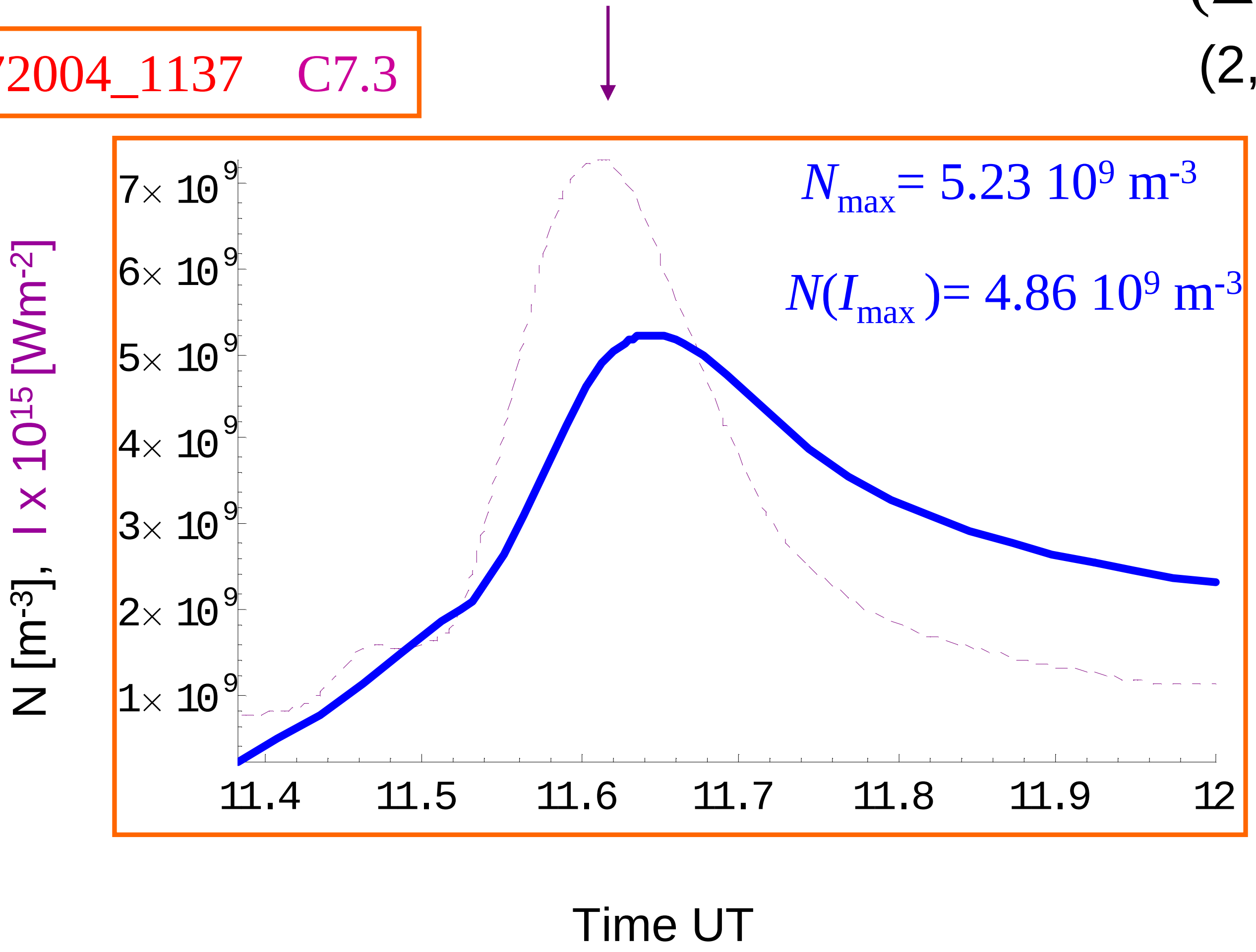
# RESULTS

## NAA/24.0 KHz

$\alpha$ = 8.75 $10^{-13}$ $m^3$ $s^{-1}$
$q(t)$ = 3.73 $10^{12}$ $I(t)$ [$m^{-3}$ $s^{-1}$]

$(\Delta t, \Delta t')$ min
(2, 1.92)

17072004_1137 C7.3



$N_{max}$= 5.23 $10^9$ $m^{-3}$

$N(I_{max})$= 4.86 $10^9$ $m^{-3}$

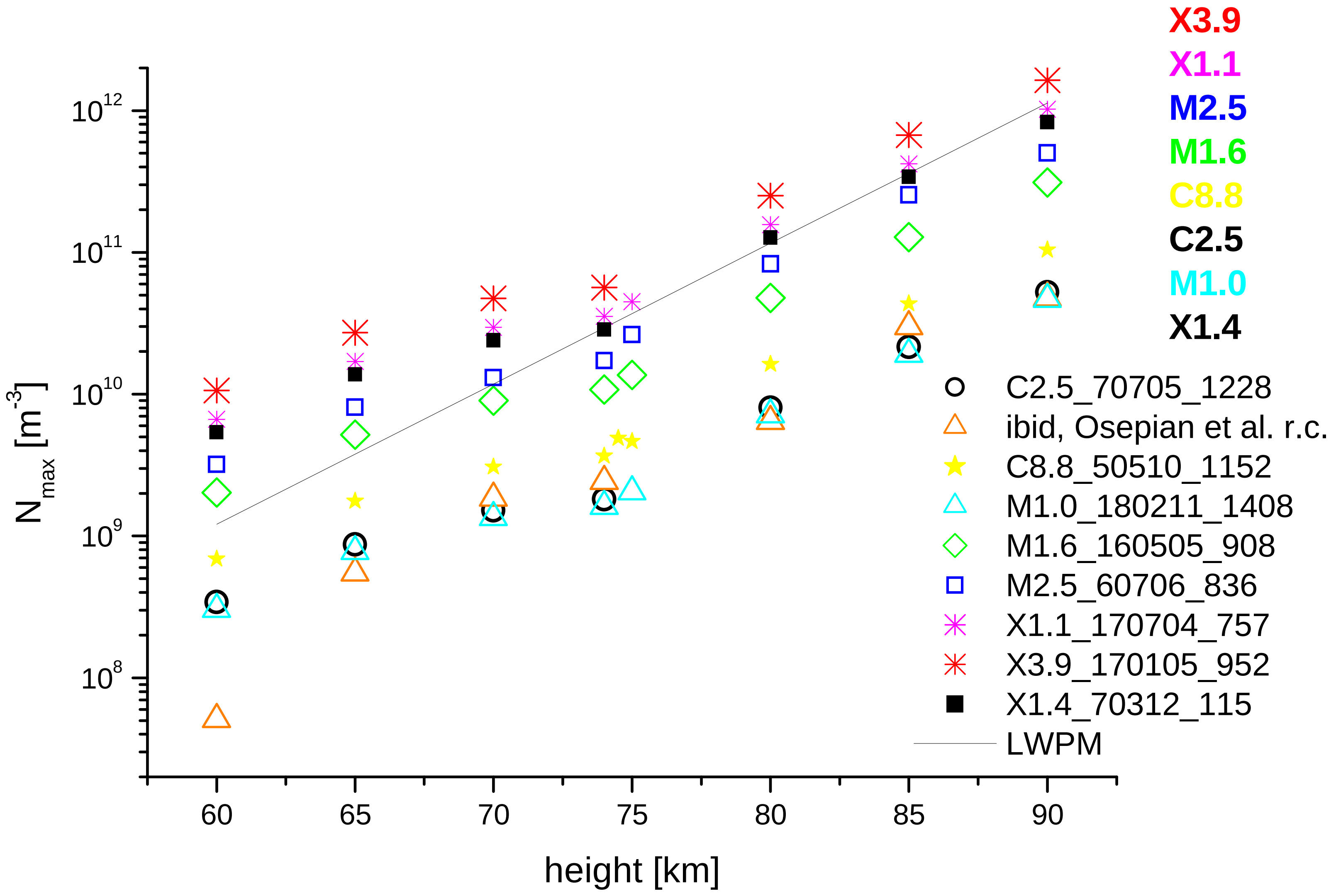
*Height:*
74 km,

$N(t=0)$:
2.18 x $10^8$ $m^{-3}$

Žigman et al., 2007,
Journal of Atm. Solar-Terrestrial Physics

Grubor et al., 2008,
Ann. Geophys

# $N_{max}$ height profile from N(t,h): $\Delta t$ from X flux 0.1-0.8 nm



# How to apply the N(t,h) model to Lyra data ?

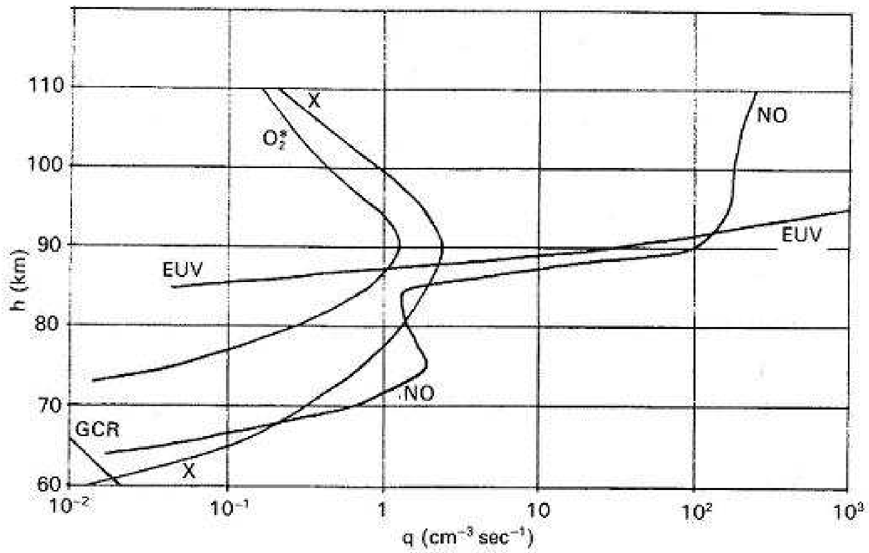


Fig. 6.13 Calculated production rates at $\chi = 42°$ due to: Extreme ultra-violet (EUV), Lyman-$\alpha$ and nitric oxide (NO), X-rays (X), Excited oxygen ($O_2^*$), Galactic cosmic rays (GCR). (J. D. Mathews, private communication)

*from*: J.K.Hargreaves,1992, The solar-terrestrial environment

Production rate / irradiance for vertical incidence at **90 km** for **6-20 nm**

$$k \cong 10^{12} \text{ [mJ]}$$

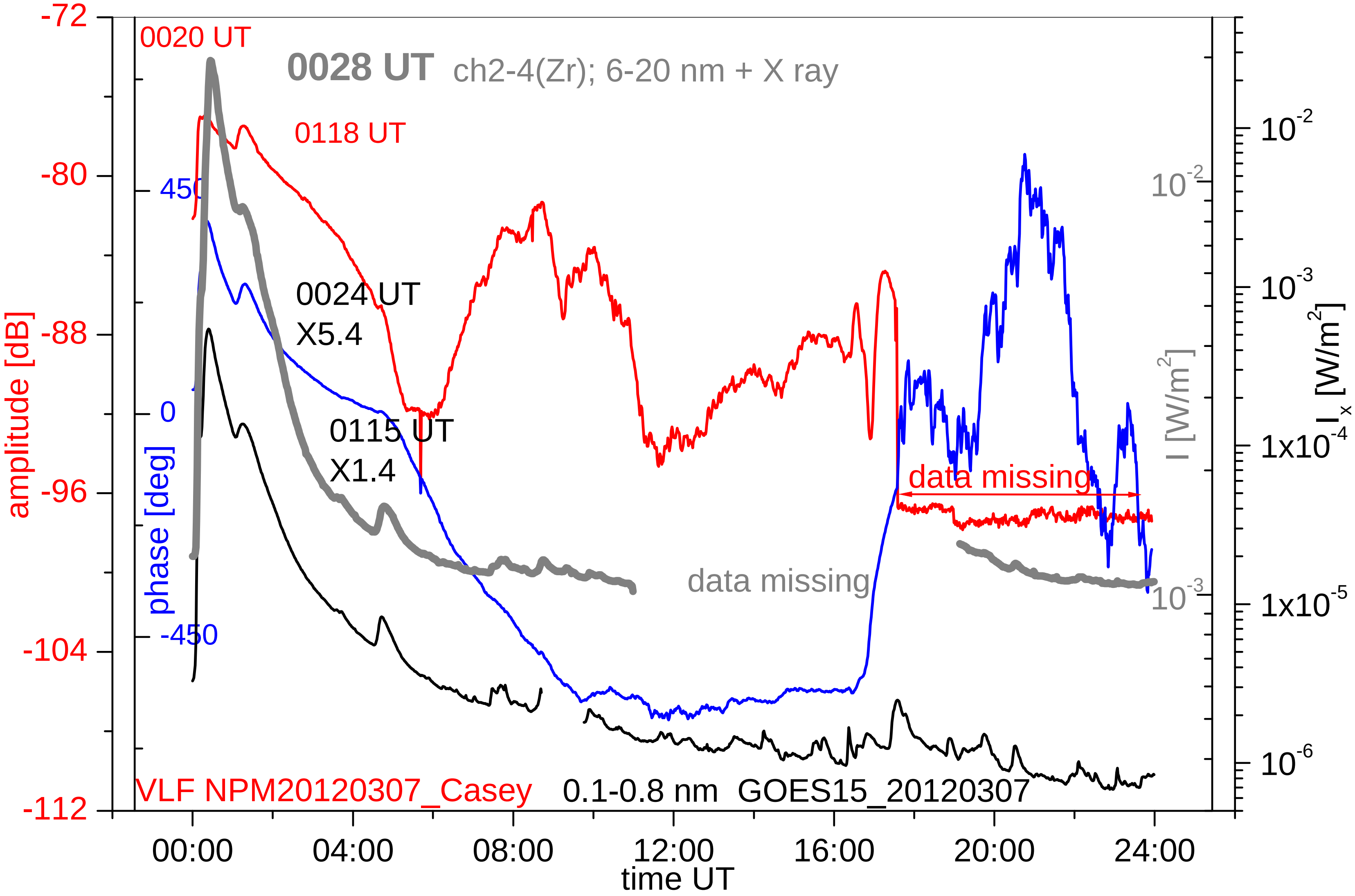
Local ionization efficiencies ?

How they change with:

- Wavelength
- Height

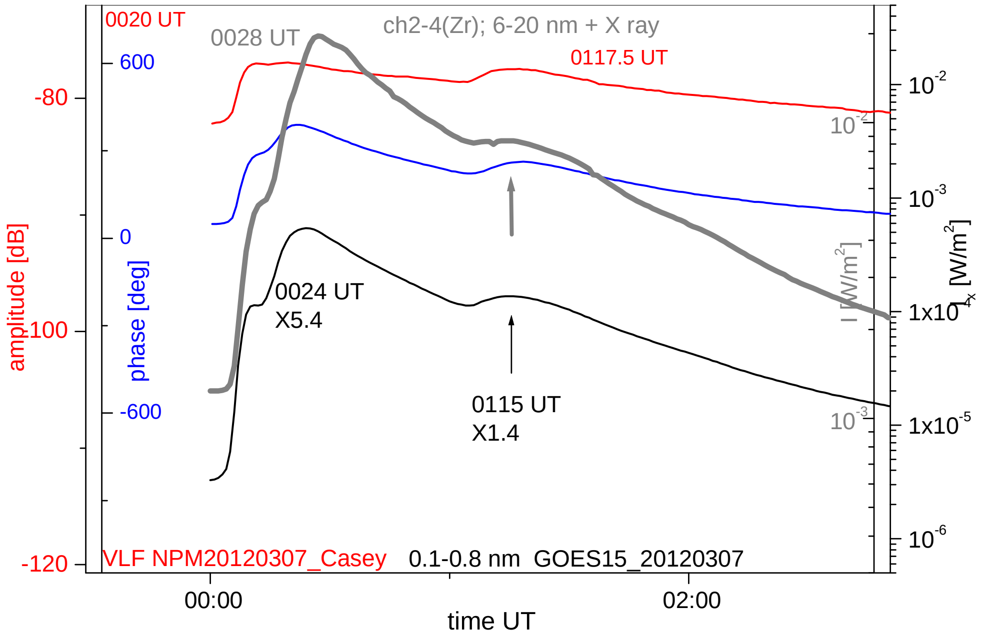
**Ohshio M, et al. 1966**
Height distribution of local ionization efficiency, Journal of the Radio Research Laboratories, 13, no 70, 245- 261

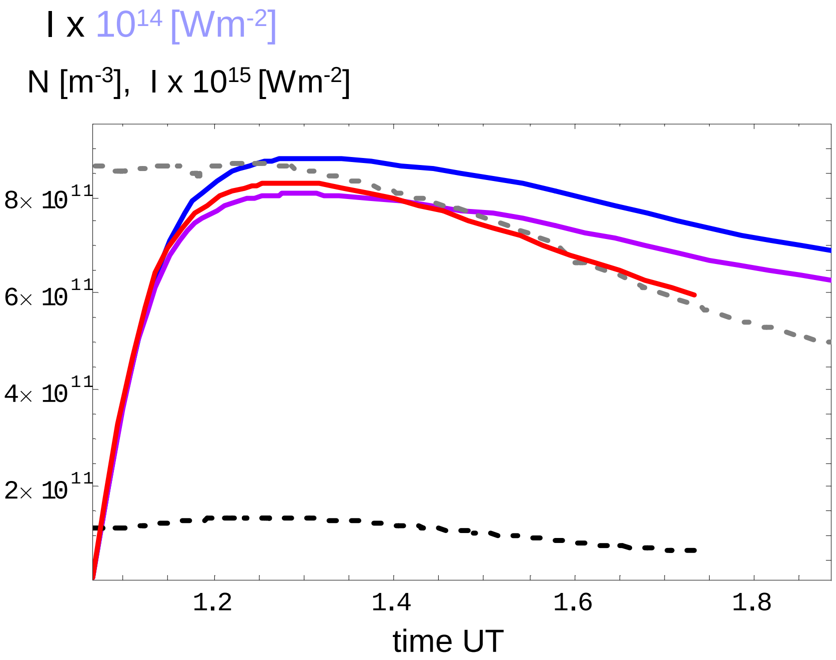
# 2012_03_07


0020 UT
0028 UT ch2-4(Zr); 6-20 nm + X ray
0118 UT
0024 UT
X5.4
0115 UT
X1.4
data missing
data missing
VLF NPM20120307_Casey
0.1-0.8 nm GOES15_20120307
amplitude [dB]
-72
-80
-88
-96
-104
-112
phase [deg]
450
0
-450
I [W/m$^2$]
$10^{-2}$
$10^{-3}$
$I_x$ [W/m$^2$]
$10^{-2}$
$10^{-3}$
$1x10^{-4}$
$1x10^{-5}$
$10^{-6}$
00:00
04:00
08:00
12:00
16:00
20:00
24:00
time UT

# 2012_03_07_0115_X1.4 H=90 km : I(t), N(t)

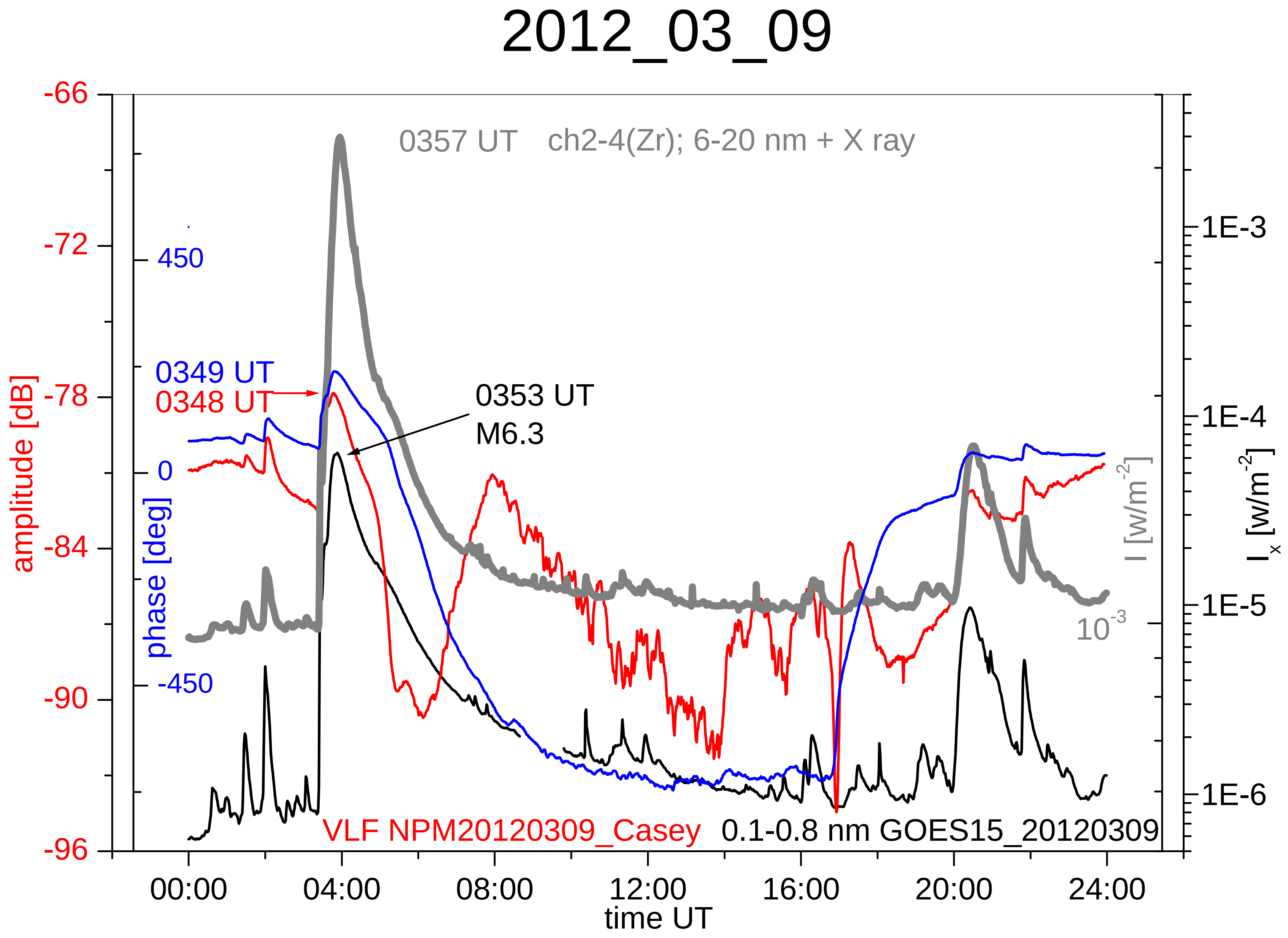
**GOES - LYRA**





| | **GOES** | **LYRA** |
|---|---|---|
| ($\Delta t$ $\Delta t'$) [min] | (2.5, 2.52) | (2.5, 2.36) |
| $t(I_{max})$ UT | 0115 | 0115 |
| $N_{\max}$ [m$^{-3}$]: AMP | **8.30 ×$10^{11}$** | **7.66 × $10^{11}$** |
| $N_{\max}$ [m$^{-3}$]: PHA | | **8.82 × $10^{11}$** |
| $N_{\max}$ [m$^{-3}$]: **LWPM** | | **1.13 × $10^{12}$** |

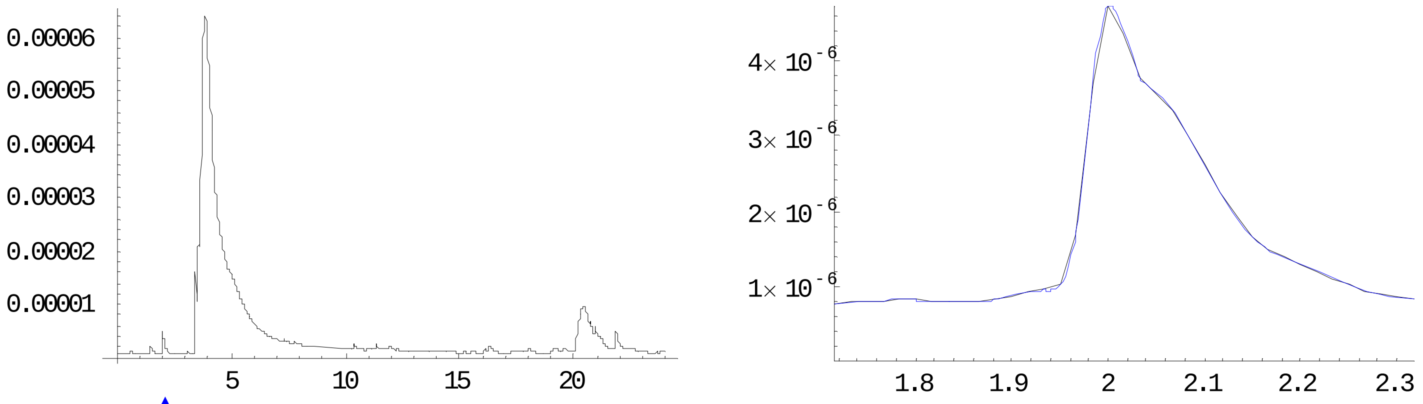
N(t) according to LYRA decreases slower than N(t) according to GOES


2012_03_09

0357 UT ch2-4(Zr); 6-20 nm + X ray
0349 UT
0348 UT
0353 UT
M6.3
VLF NPM20120309_Casey
0.1-0.8 nm GOES15_20120309
amplitude [dB]
-66
-72
-78
-84
-90
-96
phase [deg]
450
0
-450
I [w/m$^{-2}$]
$10^{-3}$
$I_x$ [w/m$^{-2}$]
1E-3
1E-4
1E-5
1E-6
00:00
04:00
08:00
12:00
16:00
20:00
24:00
time UT

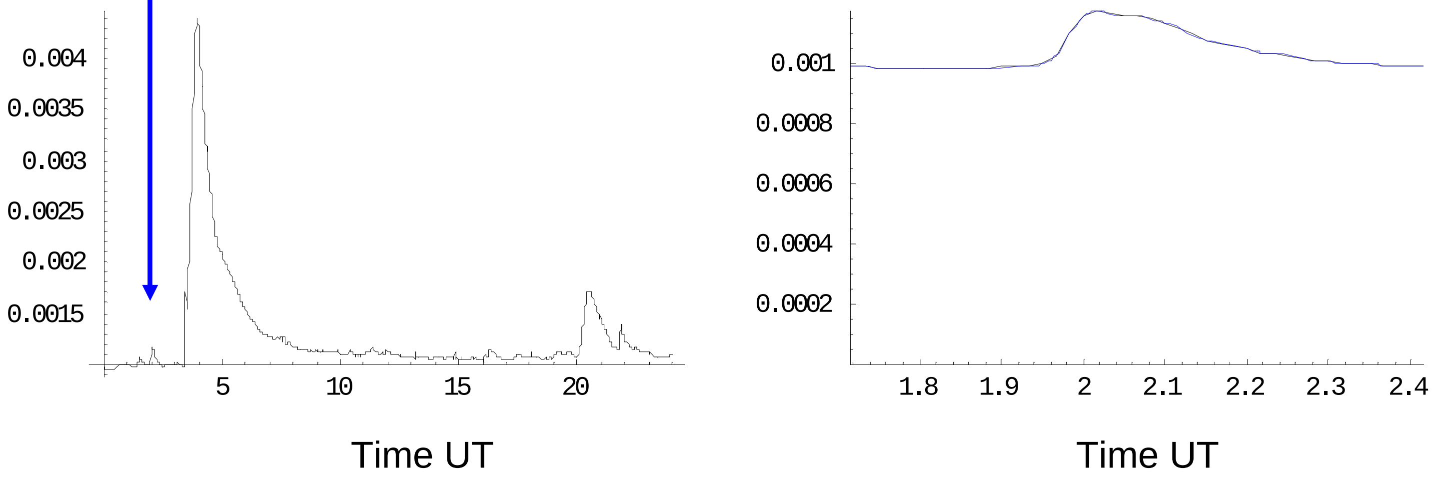
# Irr [W/m$^2$] on 2012_03_09

## GOES15   0.1- 0.8 nm;   0200 UT_C4.7

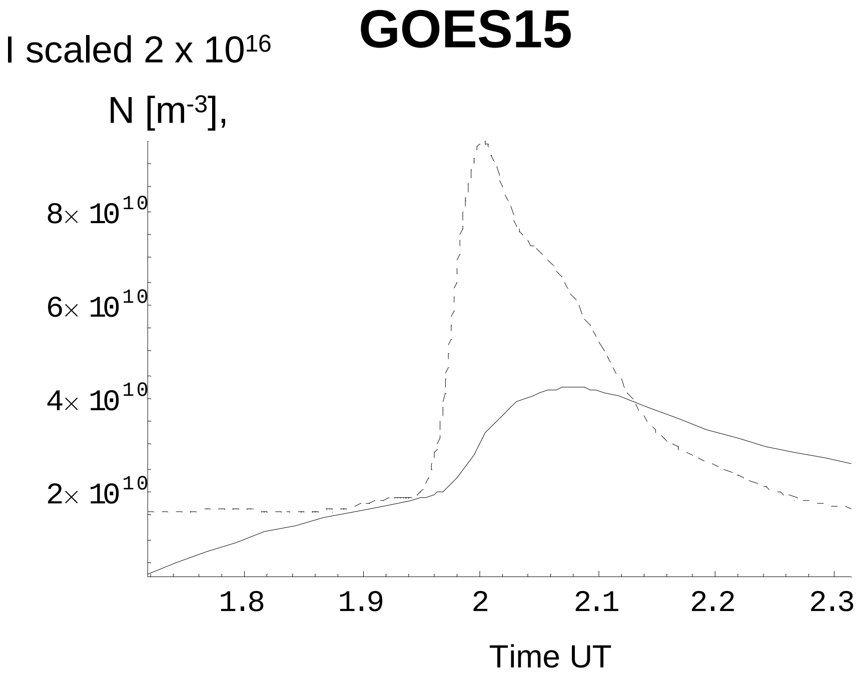


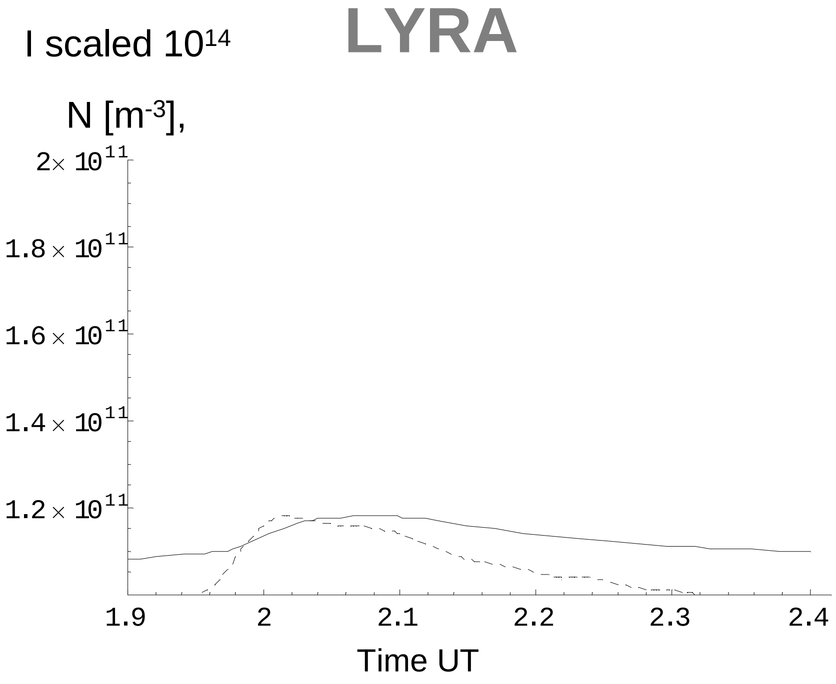
## LYRA ch(2- 4) 6 - 20 nm +Xray

### Lyra peaks at 0201 UT



# 2012_03_09_0200_C4.7 H=90 km : I(t), N(t)





| | | |
|---|---|---|
| $(\Delta t\ \Delta t')$ [min] | (4.5, 4.6) | (3.5, 3.8) |
| $t(I_{max})$ UT | 0200 | 020**1** |
| $t(N_{max})$ UT (ev) | 2.079 | 2.08 |
| $N_{\max}$ [m$^{-3}$]: | **$4.22\times10^{10}$** | **$1.17\times 10^{11}$** |

$N_{\max}$ [m-3]: **LWPM** **$3.92\times10^{10}$**

***N***s according to both **GOES** and LYRA peak **simultaneously**

# REMARKS

- X-ray flare ionization is efficient in the range 60-90km, more efficient than any other radiation in the lower D-region.
- At the D-region upper limit Ly-Alpha and EUV are more efficient.
- The diagnostics by Lyra time delay is more appropriate for the D-region upper limit, and is expected to give more realistic N estimates.
- Apparently there is no reason to retrieve N from GOES at 90 km height. But GOES time delay will give more realistic values of N for 74 km height and below.
- VLF data A and P give N ( 60- 90 km) independetly of the particular radiation. A na P bear the integral signature of the event.

# Summary

To estimate D- region electron density enhancements during Solar X-ray flares, as diagnostic tools use:

- For the lower D-region limit and its vicinity - GOES X-ray data
- For the upper D-region limit - LYRA data
- For the whole D-region  - VLF data

# Thanks to

Proba2 Science Centre

LYRA team Ingolf Dammasch

Antarctica logistic providers