

RENU2 Mission Overview

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Current as of 12 Apr 2016

This paper is intended to be a repository to summarize the RENU2 mission, including information about the launch conditions, trajectory, data and instrumentation (including both ground and onboard instruments). *At this point, the information contained in this document is considered proprietary.*

1 Launch overview

Launch took place on Dec 13, 2015 at 07:34:00 UT. Conditions leading up to launch consisted of the development of a series of PMAFs. These were observed without a strong sign of cusp aurora, presumably because the positive B_y kept the cusp further to the east of us and the PMAFs were propagating to the northwest, which is consistent with what we were seeing. Magnetic noon occurs at approximately 09:00 UT, so this seems to make sense. During the minutes before launch, Cutlass Radar signatures were intermittent but seemed to show hints of us being in the cusp, with stronger cusp-like signatures a bit to the east of us. Not long after launch, these signatures became quite a bit stronger (so I am told, but I wasn't watching that data).

During the fourth stage, the payload took a right turn and went 2.8 sigma to the right. This, it turns out, was very good for us. The planned trajectory would have been fine, but the drift to the east 1) brought us over brighter 630 nm emissions and 2) meant that the payload cut through the arc obliquely as it dropped in altitude, providing LOTS of interesting data. The unexpected trajectory did result in an apogee of only 447 km, as opposed to the planned 500 km. Remember, the idea was that apogee occurs to the south of EISCAT, so the plan was to descend as parallel to the EISCAT magnetic field as possible.

The payload reached apogee at T+409, which was very close to nominal so it does seem like we descended down along the arc in some sense (or maybe along a set of adjoining arcs). Preliminary quick-looks show electron precipitation beginning near T+442 and lasting until T+655 (200+ seconds of data within an arc!?). It may be the case that we hit re-entry while still inside the arc. Finally, there is also an electron heating event around T+335 to T+370, though with no obvious precipitation at that time.

We have excellent allsky camera data, EISCAT and Cutlass data, in addition to other ground instruments from KHO.

2 Payload instrumentation

Here are the descriptions of the various instruments (grabbed from the proposal, so maybe not quite "as flown"). This is included here for general information, but descriptions of instrument problems will be added as we move forward. All instruments seemed to have worked as intended, though the onboard imager was swamped by sunlight.

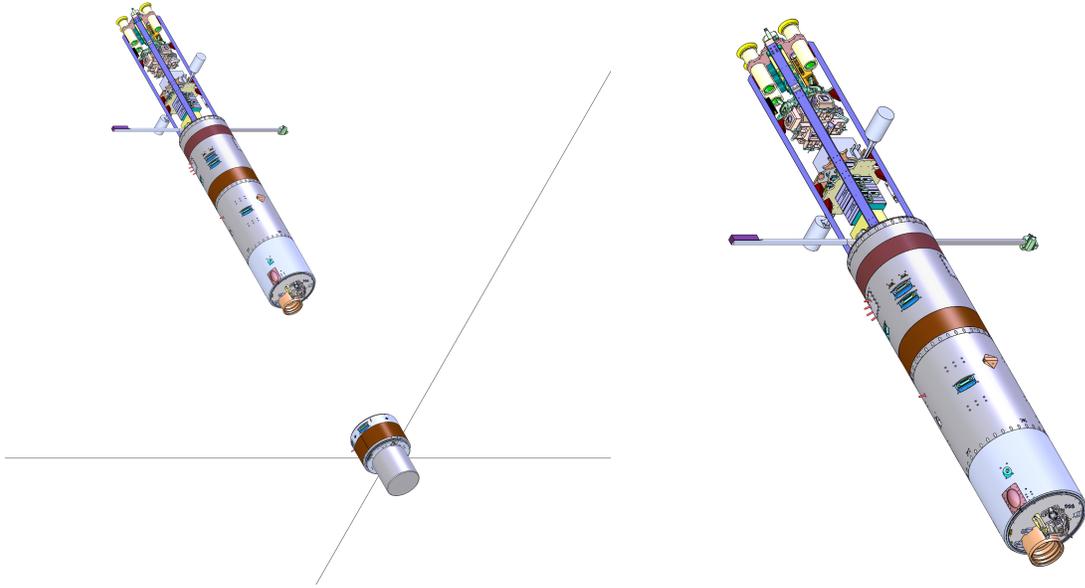


Figure 1: This figure shows SolidWorks drawing of the payload. I can add labels to show instrument locations, if needed.

Instrument	Institution	Measurement	Range
Ion Gauges	Aerospace	Neutral density and temp	$\geq 10^{-10}$ T
PMTs	Aerospace	N_2^+ (391.4 nm), O (630.0, 844.6 nm)	30 cts/s/R
EPLAS	UNH	3D distributions, precip. electrons	6 eV - 15 keV
HT - Thermal ions	Dartmouth	3D distributions, ambient ions	0.06-3 eV
HM - SuperT Ions	Dartmouth	3D, upflowing ions	6-800 eV
BEEPS - Ion mass	Dartmouth	3D, upflowing O^+ , H^+	6-800 eV
Ion Mag Spec	Aerospace	???	??
ERPA (2)	UNH	Cold electron temps (and density?)	0.06 - 3 eV
COWBOY E-Fields	Cornell	Onboard electric fields	0-20 kHz, 0-1000 Hz
Billingsley mag	Cornell	3-axis fluxgate	$\pm 60,000$ nT
Racetrack Mag	UNH	3-axis fluxgate, 24-bit (30 pT)	$\pm 60,000$ nT
Imager	UNH	630 nm images, below the payload	
UV-PMT	UNH	O (130.4 nm), 12° FOV, above	TBD

Table 1: RENU2 instruments and quantities measured.

3 Trajectory

Figure 2 shows the actual payload trajectory. The near-vertical dotted lines are IGRF magnetic field lines; the gold line is the sunlight terminator, calculated step-by-step through the flight. The payload reached sunlight at T+88 and returned to darkness near T+650. The location of the PMAF is based on the in-situ electron data (and confirmed by the allsky camera data). All of these numbers are quite close to planned trajectory, except that the

Instrument	Contact	Measurement
EISCAT	Kjellmar Oksavik	Ion T , v ; Electron T , n ; along \mathbf{B} , to $\sim 400+$ km
KHO	Fred Sigernes, et al.	Auroral cameras, MSP and high-res spectrometers
Oslo Allsky Cameras	Jøran Moen	630.0 & 557.7 nm, at both LYR and NAL
Cutlass (SuperDARN)	Tim Yeoman	Ionospheric flows (convection) and irregularities
Fluxgate Mag	??	Ground-based fluxgates at LYR, NAL and HOR
Induction Coil Mags	Marc Lessard	0-1 Hz dB/dt; EMIC waves, etc., from Hornsund

Table 2: Groundbased sources of data that directly supported this mission.

Satellite	Transit	Measurement
ePOP	East of Svalbard, at 0928 UT	Ions, electrons, waves?
NOAA	Larry Paxton?	SSUSI, particles

Table 3: Satellite sources of data that coincide with this mission.

eastward drift of the payload placed it approximately 158 km from the EISCAT beam, at its closest approach which occurred near T+482.5.

The image on the right (of Figure 2) is from the Univ of Oslo allsky camera in Longyearbyen, with the track of the payload superimposed. The track shown is the expected trajectory, but just from mapping latitudes and longitudes (no magnetic mapping in this case). See Section 5 for more information regarding allsky data and the payload trajectory.

4 Moving forward...

Figure 3 shows electron precipitation from the EPLAS instrument. Time after launch is on the horizontal axis, energies are plotted along the vertical axis and color represents fluxes (counts). The plot shows a good summary of the flight, except that EPLAS missed the heating event at around T+335 to T+370. This plot is now from the Svalsat TM and contains the entire flight. In addition to the additional data, this plot also includes time stamp and dead-time corrections. **IMPORTANT:** we are taking the launch time to be 7:34:00.000 UT and are using the data from the Svalsat TM for consistency.

In any case, it's easy to see that we caught a beautiful event, dropping down the field line as planned. The time of interest starts near T+442, lasting until T+655. In order to make good progress on the data analysis, we plan to do a few things.

1. Post summary plots at http://mirl.sr.unh.edu/projects_renu2/FlightData/FlightData.html. Login is RENU2, password is Upwelling. Bruce has already posted plots from 3 of our instruments. Please send similar summary plots to Bruce Fritz (bav66@wildcats.unh.edu), with comments about what is being shown as seen in the examples on the website). Please make these PDF or PNG files so that we can see good quality plots. Also PLEASE INCLUDE REASONABLE LABELS ON THE PLOTS!! POINTS WILL BE DEDUCTED FOR POOR AXIS LABELING!

2. It would be very helpful to be able to stack plots of data from any or all of the various

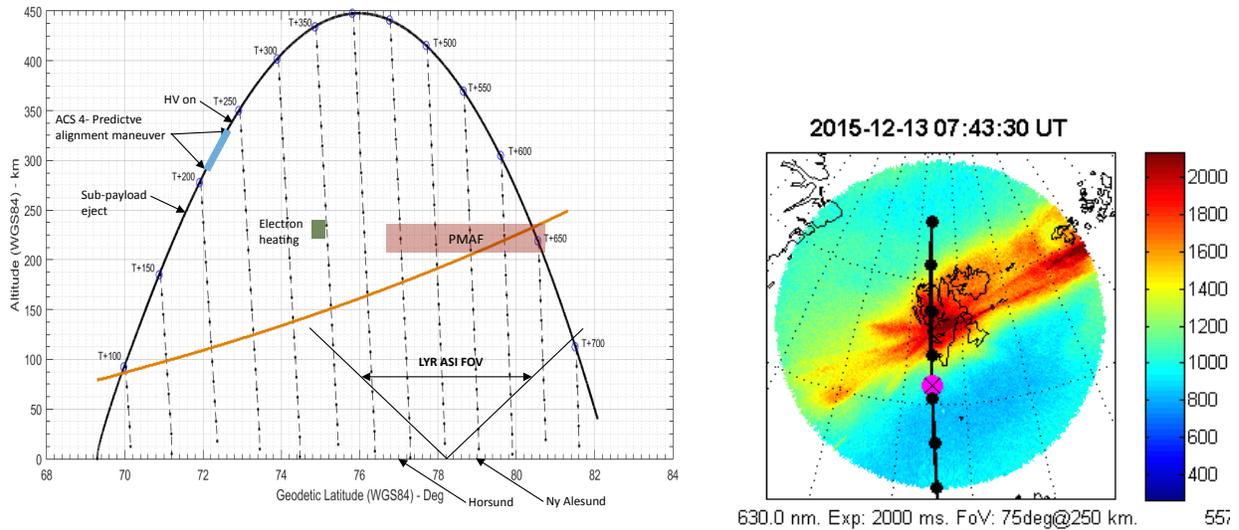


Figure 2: This figure shows the trajectory. On the right, the Oslo allsky camera that coincides with T+570, the the payload was near 340 km altitude, on its downleg, just to the north of Ny Alesund (needs to be confirmed and made more precise).

instruments. Probably the easiest way to do this is for us to provide an IDL save file (if you are using IDL) or a .mat file if you are using MATLAB that can be easily read in and plotted. I am hoping that we can do this for all of the instruments. Send the files to Bruce and he will post them to the website but will also compile a “big picture” plot showing data from all of the instruments on a single page.

3. Finally, about publications... as we make progress on the data analysis, I think it will be very important to talk to each other to make sure we are not competing amongst ourselves. Also, it looks like there will be several papers coming out of this launch and I wonder if we should consider (after we have a deeper understanding of what the data really can tell us) the possibility of a GRL special issue, as was done with the SCIFER mission. Finally, I realize that people make have concerns about data ownership and am sure that we can make this all work out.

5 Optical observations.

Lasse Clausen has provided detailed (and calibrated) plots of allsky camera data. Figure 4 shows keograms extracted from the 630 nm allsky camera. The panel on the left includes data from an hour before launch to show the development of PMAFs and temporal aspects of auroral heating. Note that there was snow on the camera dome, initially. The KHO crew scrambled to clear the dome as things developed and data before about 06:42 are not reliable. The panel on the right shows details of the PMAf transited by the payload.

From Lasse: “Our imager has a resolution of 20-30 seconds; I can prepare plots of all the images we have during the flight. Note that these images are already available at <http://tid.uio.no/plasma/aurora> (click your way to the right date, and chose the appro-

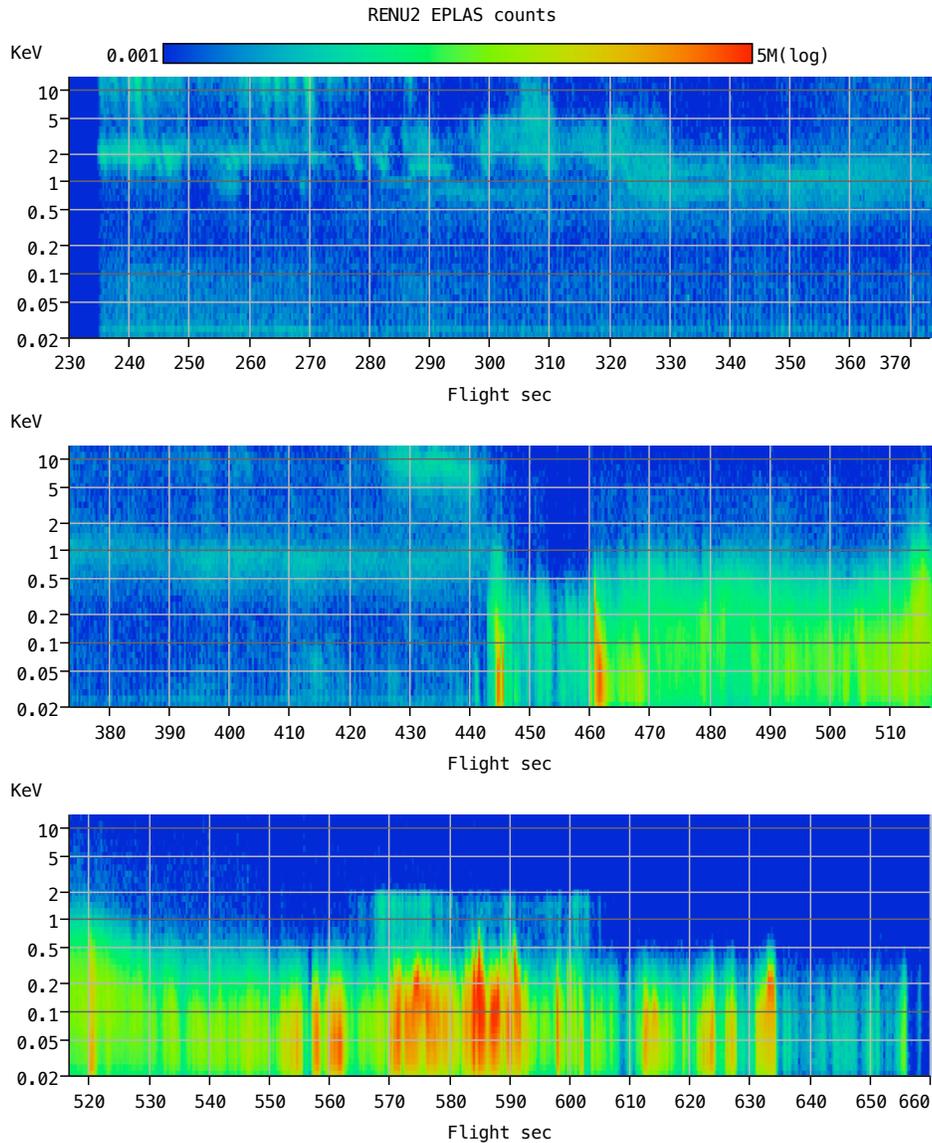


Figure 3: This figure shows the EPLAS data (electron precipitation).

appropriate hour of the Longyearbyen keogram - below it is a link “show individual images” which does just that). However, these images are individually scaled so it is difficult to compare between them - like I said, I will prepare all images on a common scale for you. You can also download the PNGs from the website and do your own analysis (click “open raw image folder” instead of “show individual images”).”

5.1 DMSP SSUSI data.

Bruce has been following up on a suggestion from Kjellmar to look at DMSP UV data. There are excellent data available from the UV imagers on F16 , F17 and F18. The imagers use a

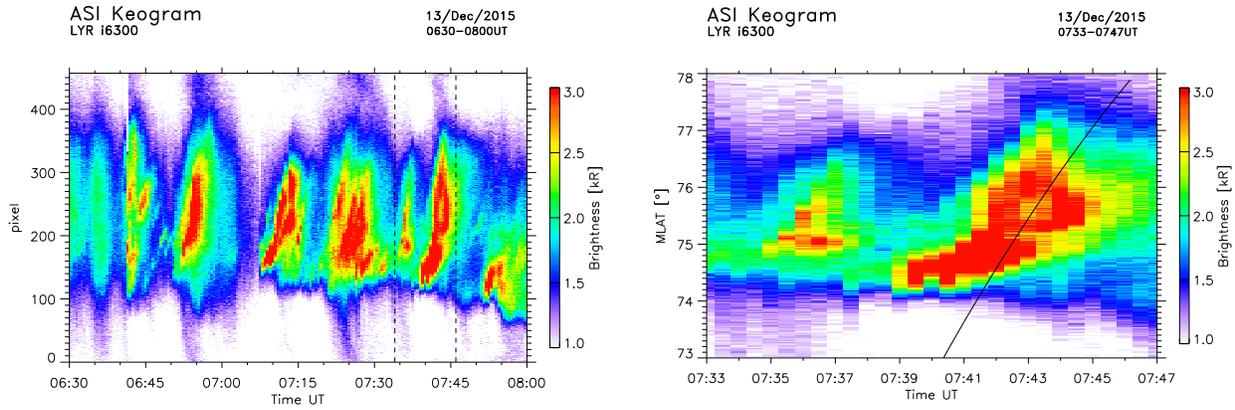


Figure 4: On the left is a keogram from the 630 nm allsky camera showing the PMAF development of the event over time (i.e., a measure of the auroral heating that took place). On the right is a zoomed-in image showing the trajectory of the rocket through the PMAF.

“pushbroom” technique, so we get one image per orbit (altitudes are near 830 km).

The imaged wavelengths include 130.4 nm (nominally from solar UV fluorescence) and 135.6 nm (nominally from electron bombardment), both from neutral atomic oxygen. The onboard UNH UV PMT instrument used a narrow bandpass filter that included both of these lines. The onboard PMT was aimed UP the field line.

Figure 5 shows an image from F18 that corresponds (we think) to the RENU2 overflight. This is just an initial effort, but you can easily see Greenland, as well as a faint white spot (Svalbard) with atomic oxygen roughly in the same vicinity as the PMAF. On the right side of that figure is the data from the UNH PMT, where you can see these same emission lines as the payload passed over the PMAF.

There is still a lot of work still to do with these data, but it seems clear that the satellite observed atomic (neutral) oxygen below the spacecraft, while RENU2 saw similar emissions as it looked UPWARDS, so observed atomic oxygen ABOVE the rocket payload. Obviously, it will be important to compare the relative brightnesses of these observations in order to estimate the density but it looks like we have a very good measurement of upwelling atomic oxygen.

6 Update, early March 2016

Recent additions include 1) Cutlass and EISCAT radar plots, 2) in-situ electric fields, 3) Aerospace PMT data.

6.1 Radar data

Tim Y has provided plots of Cutlass radar, providing solid evidence that we were in the cusp during launch and also providing quantitative information about convection. Figure 6a shows an overview. More details are provide on our RENU2 website, but the bottom line

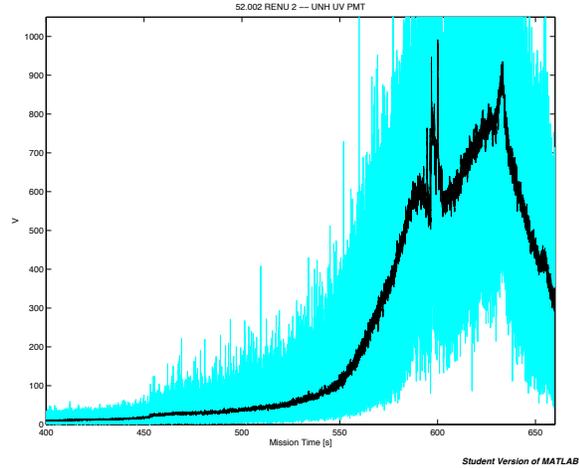
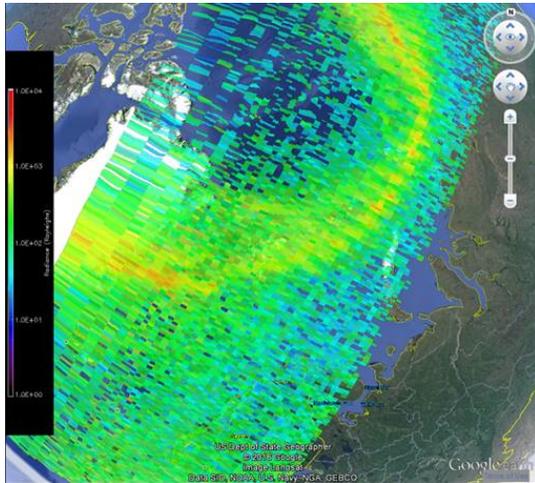


Figure 5: Left: SSUSI UV image. Svalbard is the faint white spot in the center of the image. Right: UV PMT data from onboard RENU2, now looking UP the field line, as the payload passed over the PMAF. It appears that we can show the presence of neutral atomic oxygen at altitudes roughly between 400 and 800 km altitude. Realistically, these emissions are likely at the lower altitudes - otherwise the 2D image would not map correctly, as it seems to do.

shows poleward convection (yellow pixels), typical of the cusp. Tim will also add the RENU2 trajectory to these plots.

Kjellmar has provided an improved plot of EISCAT radar. From his email, "I have reanalyzed the EISCAT data with different resolution, and I found that 120 seconds integration gave the best temporal resolution vs. signal-to-noise."

In Figure 6b you see:

1. There were several transient enhancements in the electron density, and around launch we only saw the F-region (consistent with the cusp).
2. Throughout the interval there were several transients in electron temperature, which would be consistent with PMAF activity
3. The Joule heating was mostly seen in the hour prior to launch, but there may be some weak Joule heating around 07:38 - 07:48 UT.
4. There appears to be weak ion upflow in the topside region (above 400 km altitude) throughout the interval. Around 07:34 - 07:48 UT the ion upflow appears to have been extending all the way down to 300 km altitude.

6.2 In-situ electric field data

Dave has processed onboard electric field data, shown in Figure 7. Note that these plots have time stamps from T+400 to T+680, which seems to work well because it shows a good

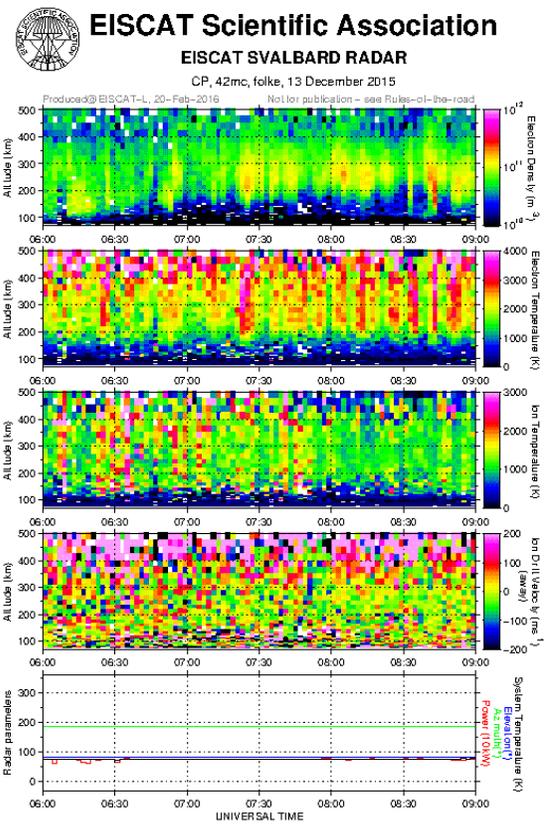
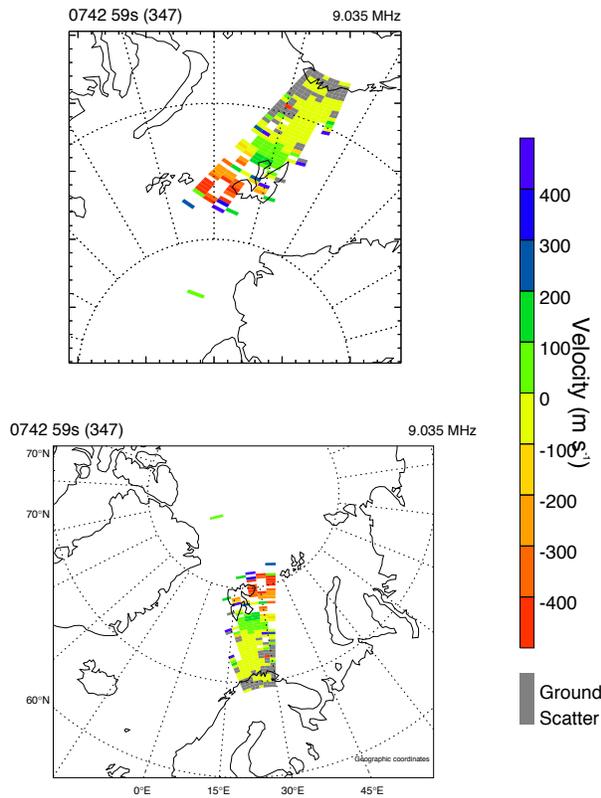


Figure 6: Cutlass and EISCAT radar data

overview of the flight with adequate detail at this point. The upper left plot shows DC fields, the upper right shows VLF wave power. The bottom left is a feather plot, showing convection, which is not very strong, which is good in the sense that it is not anomolous, and seems to show numerous counterstreaming flow channels (typical for the cusp, as I understand it). The bottom right plot shows the plasma line, which will be converted to densities.

6.3 Aerospace PMT data (N_2^+)

Jim H has a very interesting result, from the Aerospace PMT's, looking upward, above the payload. Figure 8 shows a photometer overview plot on the left. From Jim: "I have not corrected for sunlight entering the 3 channels. I believe that averages out to about 10 to 20 R. I also have not corrected for the filter transmission of the 3914 band (about 60 percent). The most noteworthy aspect is that the 3914 channel shows a sharp increase in signal around 500 s and a sharp decrease around 630 s. These sharp changes are not seen in the other two channels."

The plot on the right focusses on the 3914 channel. "The analysis is till preliminary. However, we can say a few things. Almost all of the 3914 signal is due to solar scattering

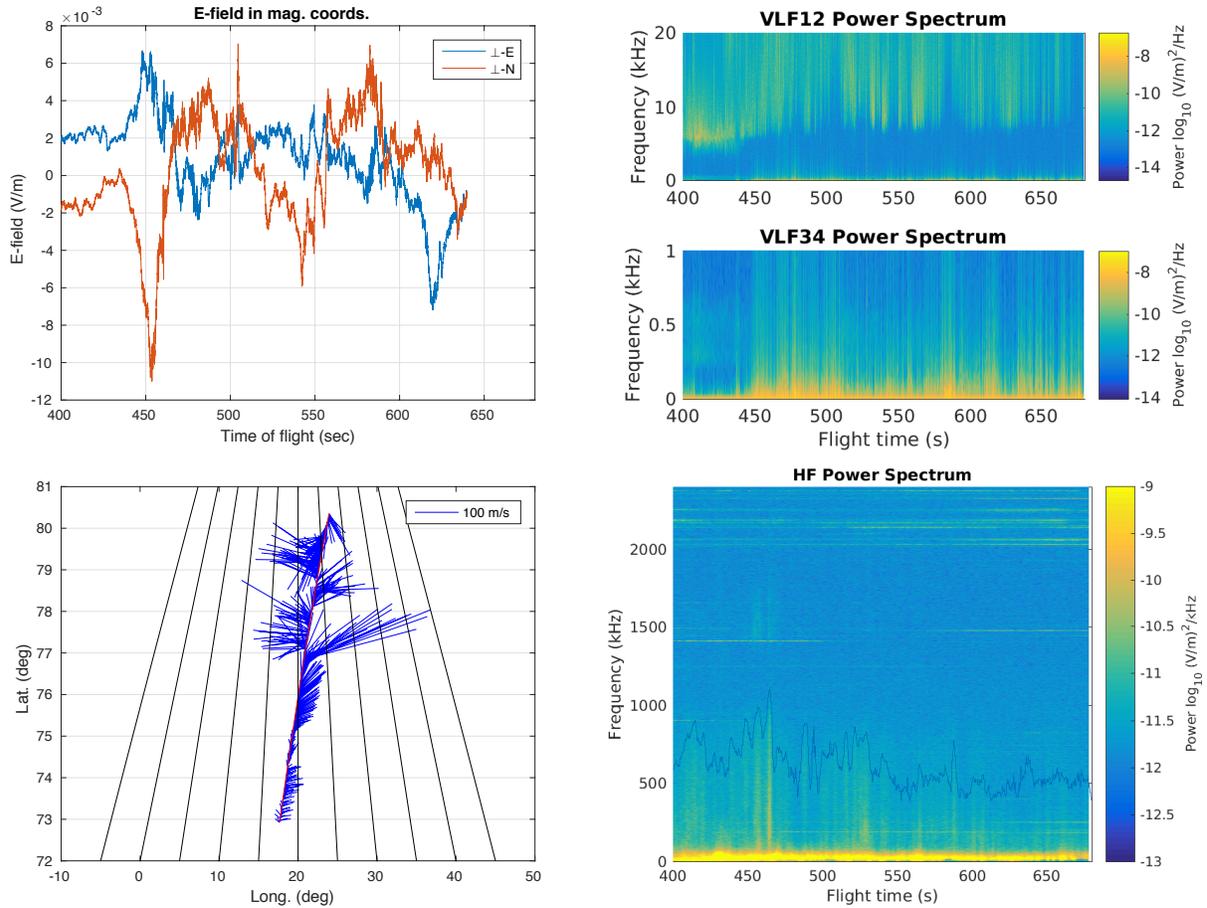


Figure 7: Cornell efield data. DC fields on the left (from which Dave has extracted convection) and VLF fields on the right (which I know very little about!). Bottom left is a feather plot showing convection along the trajectory. Bottom right is the HF data with a trace showing the plasma frequency, from which we will extract densities. This means we should have excellent measurements of density and electron temperature throughout the flight.

off N_2^+ ions. In fact the 3914 signal shown is 0.05 times the N_2^+ column above the rocket which is illuminated. I have worked with CPI to do a first cut at the 3914 day glow. That is the solid line. It over estimates on the up leg and underestimates on the down leg. This could perhaps be related to different N_2/O ratios. I also added in the extra signal due to the production of additional N_2^+ ions from the auroral precipitation. Noteworthy is that there is no sudden jump at 500 s. Is this due to a sudden change in composition or ion upwelling? Unknown at this time. We are also looking as to whether the day glow really decrease so rapidly on the downleg.”

To put things in perspective, N_2^+ ions have been associated with what is called “sunlit aurora”. This is “aurora” in the sense that it has been ionized by electron precipitation, but the luminosity comes from solar UV photons – or that it the idea, anyway. There have been reports of N_2^+ at altiudes up to 800 to 1000 km, so it seems that it must be driven

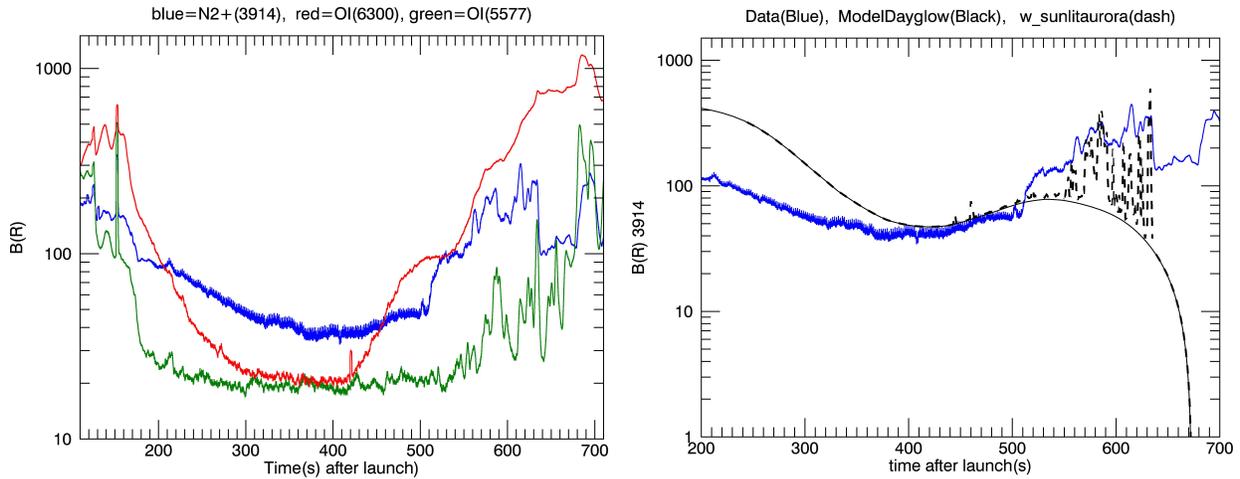


Figure 8: Aerospace PMT data.

upwards as part of the ion upflow process. Although number fluxes are something like 10% (from an older Yau paper using Akabono data), the mass flux would presumably be 20% so is significant.

It seems to me that this is an excellent result! Jim pointed out another paper on this, but it seems like the RENU2 observations are special in that they are unique in relating the sunlit aurora to ion upflow.

6.4 Modeling efforts and next steps..

As we move ahead, it will be important to keep in mind that there are significant modeling efforts that will be needed to explain the physics. When it comes to explaining the neutral upwelling, I would say that there are now 4 different (VERY different) theories. Below is a one-line description of each, along with individuals who could run the model(s)

1. G. Crowley: The upwelling is fundamentally driven by Joule heating.
A good starting point for the idea is Crowley, G., D. J. Knipp, K. A. Drake, J. Lei, E. Sutton, and H. Lhr (2010), Thermospheric density enhancements in the dayside cusp region during strong BY conditions, *Geophys. Res. Lett.*, 37, L07110, doi:10.1029/2009GL042143. *Geoff is a funded Co-I, so his involvement is certain.*
2. A. Otto: The upwelling is driven as part of the Type 2 ion outflow process.
Sadler, F. B., M. Lessard, E. Lund, A. Otto and H. Lhr (2012), Auroral precipitation/ion upwelling as a driver of neutral density enhancement in the cusp, *Journal of Atmospheric and Solar-Terrestrial Physics* 8788.
3. B. Zhang: Soft electron precipitation enhances conductivities in F-region, which enables increased Joule heating at these altitudes.
See Zhang, B., W. Lotko, O. Brambles, M. Wiltberger, W. Wang, P. Schmitt, and J.

Lyon (2012), Enhancement of thermospheric mass density by soft electron precipitation, *Geophys. Res. Lett.*, 39, L20102, doi:10.1029/2012GL053519. *I am working with Bin on a related project, funded through AFOSR (I am PI). I am sure that he would be more than happy to work with us and he is very good.*

4. Brinkman (and Clemmons): Direct particle heating plays a major role. See Clemmons, J. H., J. H. Hecht, D. R. Salem, and D. J. Strickland (2008), Thermospheric density in the Earth's magnetic cusp as observed by the Streak mission, *Geophys. Res. Lett.*, 35, L24103, doi:10.1029/2008GL035972. *This is the Aerospace connection. The modeling effort is technically not funded by the RENU2 grant but it would be crazy to not support this effort.*

In anticipation of what we will need for the modelers, I am asking the U. Oslo folks to extract luminosity at the footprint at T+600 versus time, going back to maybe an hour before T+600. The idea is that heating the neutrals takes a lot of time. In a PMAF event, the heat from electron precipitation is deposited as the arcs pass overhead. This means we would expect to “see” (from the models) the electron temperature heating and then cooling within 10-20 seconds or so, relative to the PMAF arcs. We should see the ion heating tend to average out more, because of its greater thermal mass and we should see the neutrals require the longest (integrated) heating times. But the neutrals have the greatest thermal mass, so the effect should be more smeared than for the ions. Comments on this idea are very welcome!

7 Update, early April 2016

Recent updates include a) information about the temporal aspects of electron precipitation from Lasse Clausen and 2) word from Matt Zettergren, agreeing to run his model to look at electron and ion dynamics, relationships to current closure, ion upflow, etc.

Figure 9 shows plots that Lasse provided, derived from the U. Oslo (J. Moen) allsky camera data. The two panels on the left show the brightness at the payload footprint throughout the flight, with 557.7 nm in the top panel (mapped to the 150 km footprint) and 630.0 nm in the lower panel (mapped to the 250 km footprint). The steppiness in these plots results from the integration times of the cameras, which is 15 seconds for 557.7 nm and 30 seconds for 630.0. These plots can generally be expected to show good correlations with variations onboard the payload having short timescales.

The plots on the right hand side in that figure are intended to show the temporal effects of the precipitation as the arcs drift poleward through a point that maps to the payload at T+600 seconds, which is when we seem to see heated neutrals (according to the UV PMT data). Convection speeds were ~ 100 -200 m/s so should not be ignored but I think they may be relatively insignificant.

The way these plots were done was to first identify the region in the allsky camera where the payload mapped to at T+600 seconds. Then, data were extracted (using a 20 km radius) from that region extending back to 06:40 UT with the idea that the plot should provide a measure of the temporal variations of the precipitation over that spot. The same altitudes were used as above and all mapping was done using IGRF.

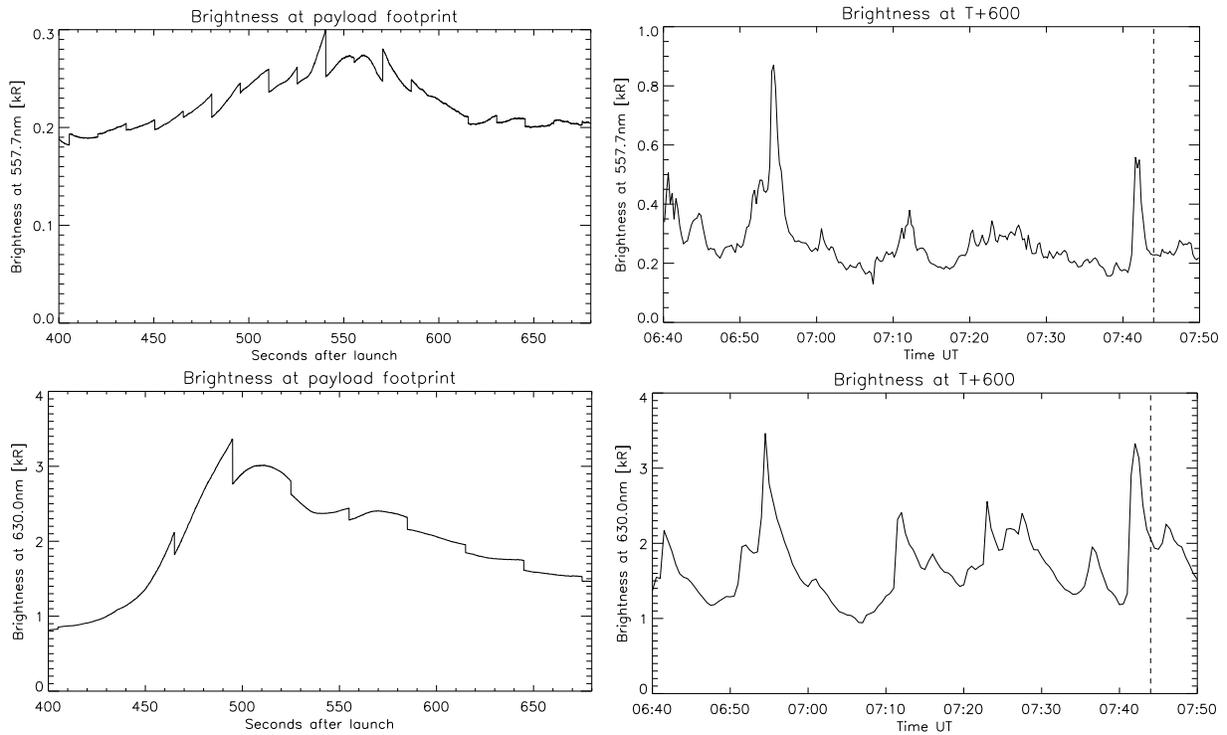


Figure 9: Footpoint plots.

The approach that I have in mind would be for the models to turn precipitation on and off in such a way as to emulate these variations. Then, we should have good comparisons at T+600 (which is marked on the plot at 07:44 UT) for electron, ion and neutral temperatures.

The data files are also posted on the RENU2 website as IDL save files containing, again for the 630.0 nm channel and the 557.7 nm channel, the brightness at the payload footprint (variable named `foot_bright` with seconds after launch in `foot_secs` or Julian day in `foot_juls` - use IDL's `JULDAY` and `CALDAT` to convert to day, month, year, etc) and the brightness at the payload location at T+600 in `t600_bright` together with the Julian day in `t600_juls`. Use as:

```
restore, 'renu2_asi_bright_i6300.dat'
plot, foot_secs, foot_bright
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