Air Force Research Laboratory

Empirical Modeling of Plasma Clouds Produced by the Metal Oxide Space Clouds (MOSC) Experiment

Ionospheric Effects Symposium

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T. Pedersen

Space Weather Center of Excellence

Space Vehicles Directorate

Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Co-Authors and Acknowledgements

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Outline

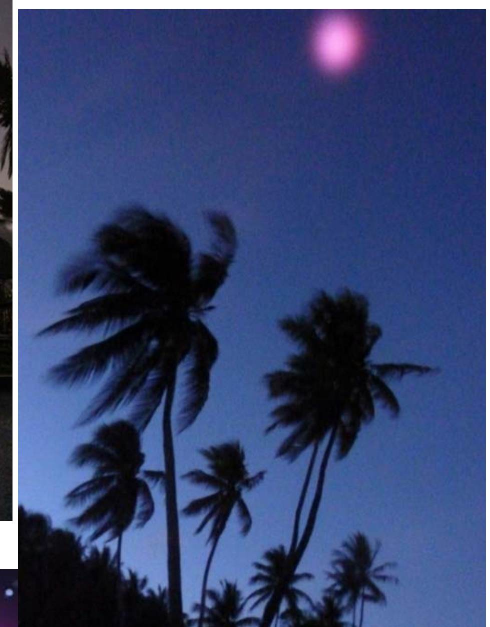
- MOSC experiment overview
- Diagnostic instrumentation
- Fitting of optical data
  - Amplitude
  - Position
  - Widths
- Comparison with ALTAIR radar data
- Peak plasma density as a function of time
- Findings and discussion
- Summary and conclusions

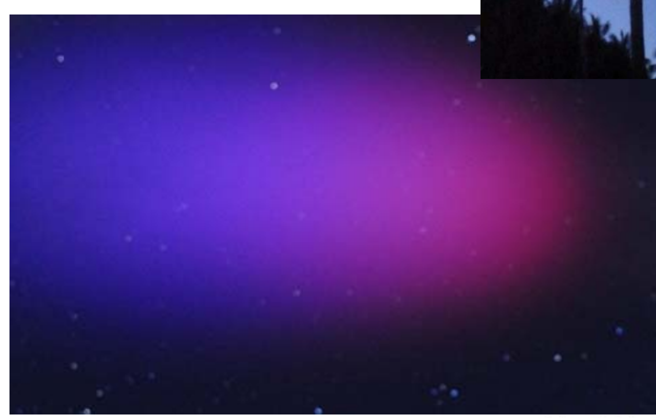
MOSC Experiment Overview

- 2 Terrier-Orion rockets funded by DoD Space Test Program
  - Launch from Kwajalein Atoll May 2013
    - Launch 1 07:38 UT May 1, 2013
    - Launch 2 07:23 UT May 9, 2013
- Primary objective: examine feasibility of using artificial plasma to short out Rayleigh-Taylor instability
- Released 2 Samarium canisters each, total of ~6 kg per launch
  - Produce plasma via chemionization:

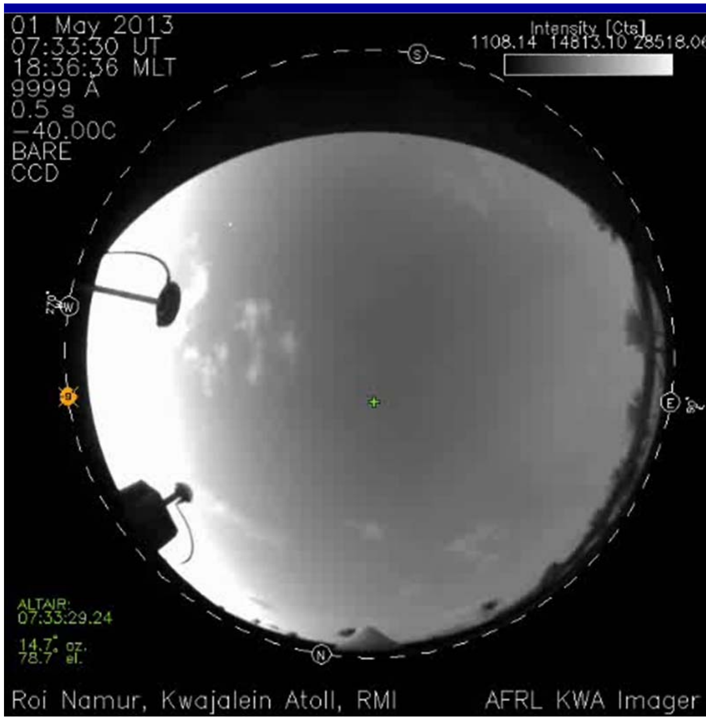
$$Sm + O \rightarrow SmO^{+} + e^{-}$$

- Ground diagnostics from 5 islands including:
  – Incoherent Scatter Radar, GPS/VHF Scintillation RX, All-Sky Cameras, Optical Spectrograph, Ionosondes, Beacon RX, HF TX/RX





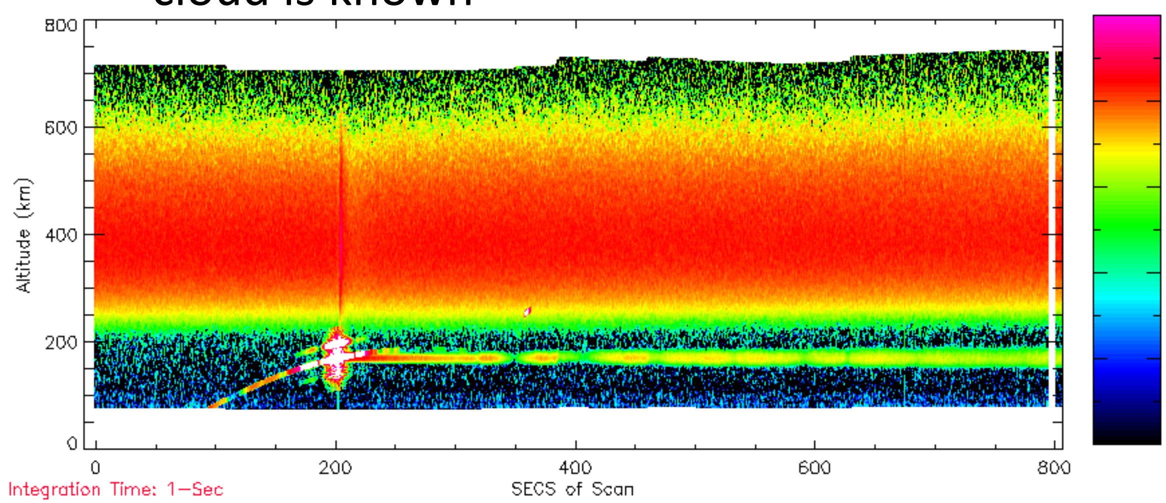
Radar and Optical Data



Movie of radar scan in optics

Optics provide critical context for radar measurements

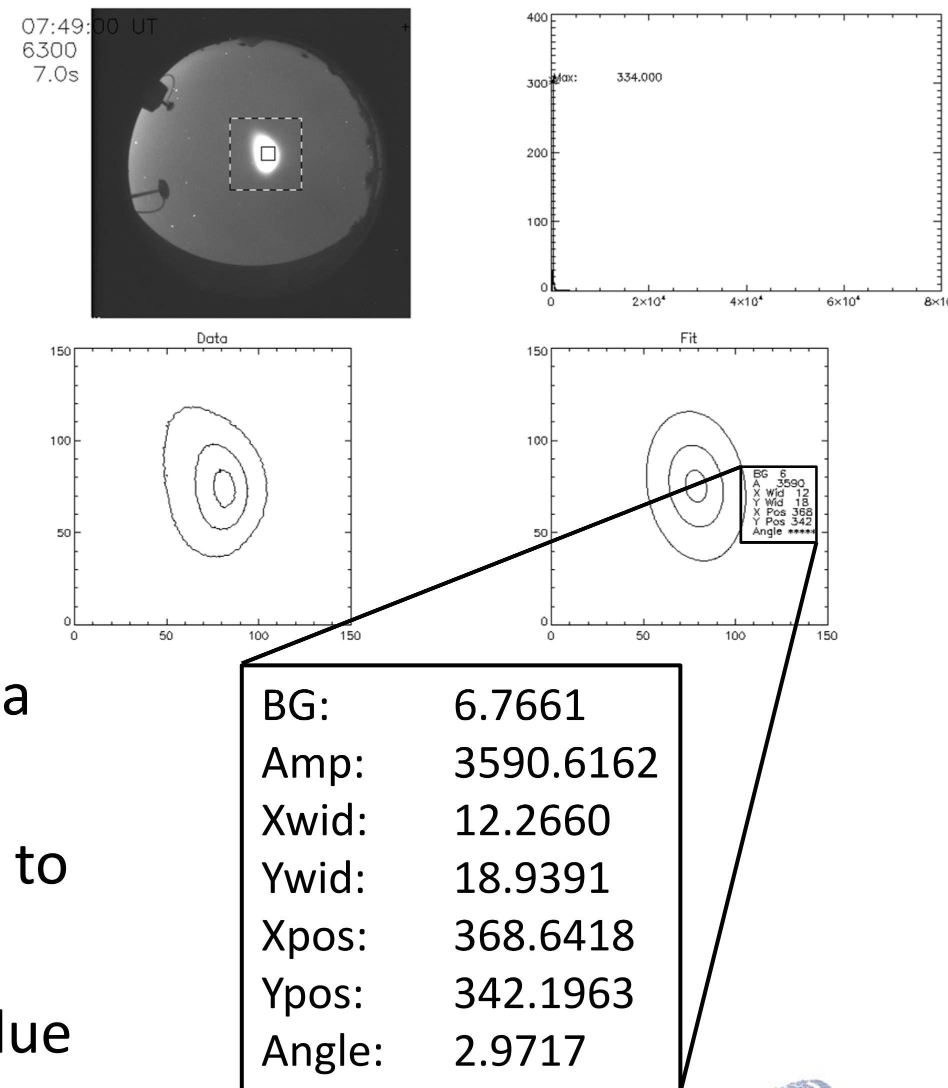
- ALTAIR radar pointed at expected release location
- Pre-programmed raster scan locations updated in real time based on optics
- Radar electron density modulated in time as radar scans across cloud
  - But of limited utility unless position relative to cloud is known



Radar densities vs. time and altitude

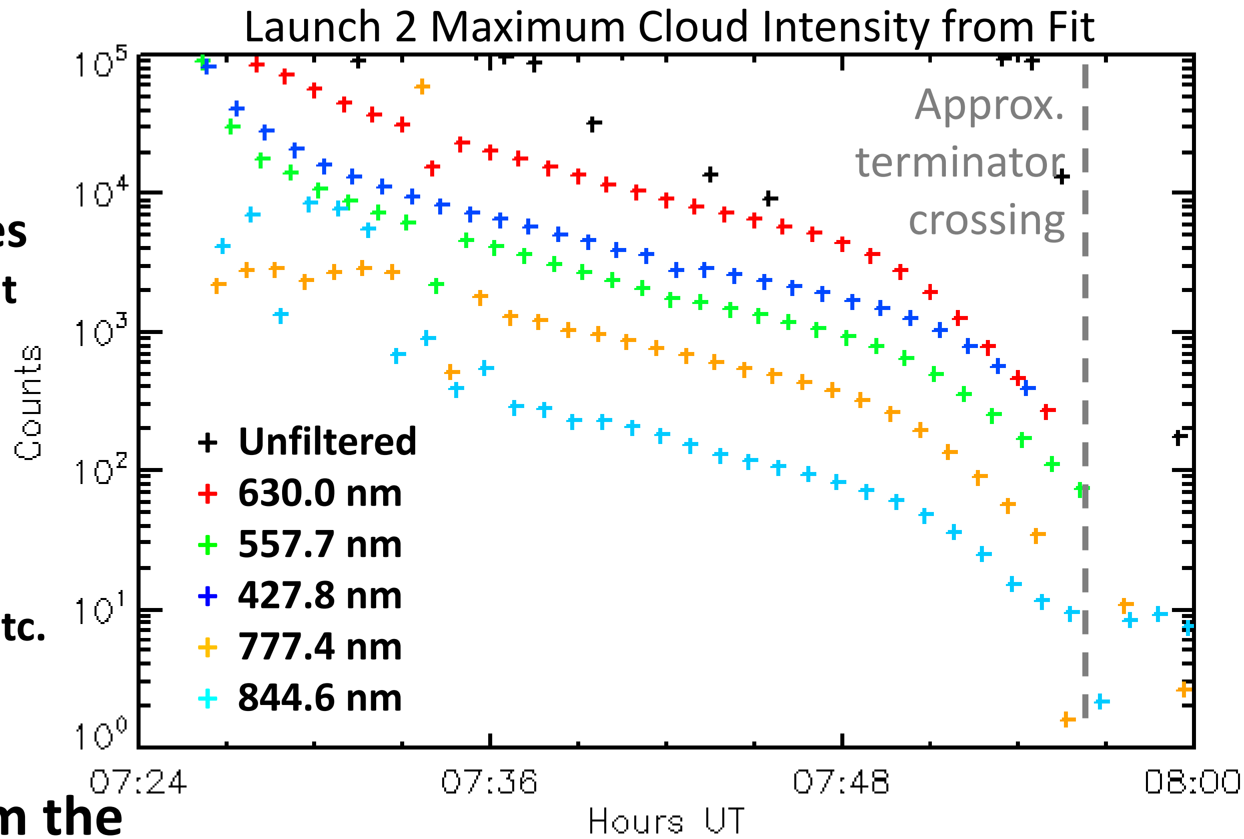
Empirical Model Construction

- Fit optical data to 2-D Gaussian distribution as function of time
  - Provides the following properties
    - X, Y locations (in pixels)
    - X,Y halfwidths (in pixels)
    - Peak optical intensity
    - Background intensity
    - Tilt relative to principal axes
- Fit low-order polynomials to data as function of time
- Fit relative optical intensity data to radar TEC and plasma density
  - Absolute intensity changes due to twilight, clouds, etc.



Optical Intensity Fits

- **Not actually used in model**
  - **Absolute intensity has too many dependencies**
    - **Rapidly changing twilight background on ground**
    - **Rapidly changing illumination of clouds at altitude**
    - **Filters not tuned for relevant wavelengths**
    - **Clouds, light pollution, etc.**
  - **But good indicator of data quality**
- **Absolute intensities from the various filters track each other very well**
  - **Unfiltered channel overexposed most of the time**
  - **Wild points generally due to passage of tropospheric clouds**

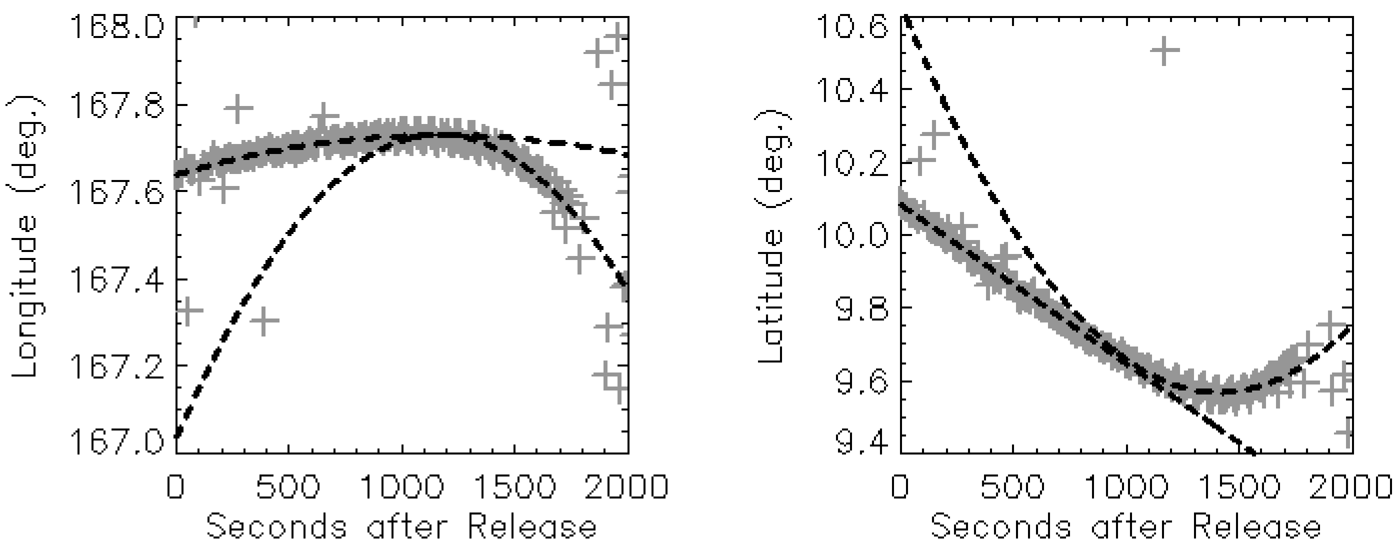


- **Fitting process very consistent across 4 orders of magnitude and 6 wavelength channels**

Position Fits

- **Data originally in pixel coordinates**
  - **Convert to lat, lon**
    - **Calibrate images to azimuth and elevation**
    - **Use release height to map from az/el to lat/lon**
- **Good piecewise fits using low-order polynomials**
  - **Break point near 1000 sec**
  - **Linear or parabolic**
- **Slight differences between wavelengths**
  - **This fit for all wavelengths combined**

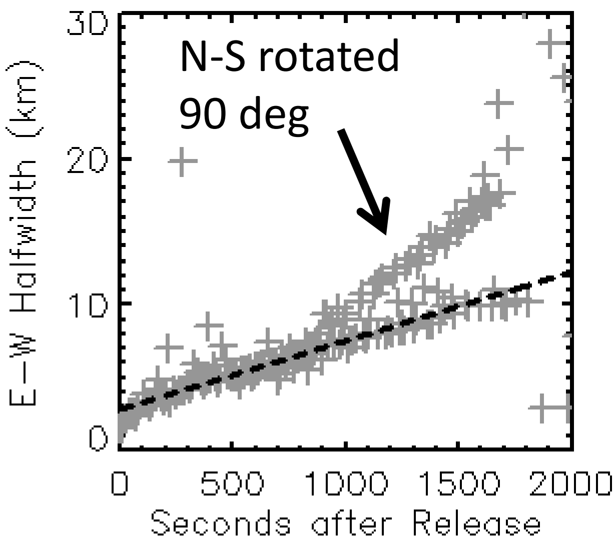
Launch 2

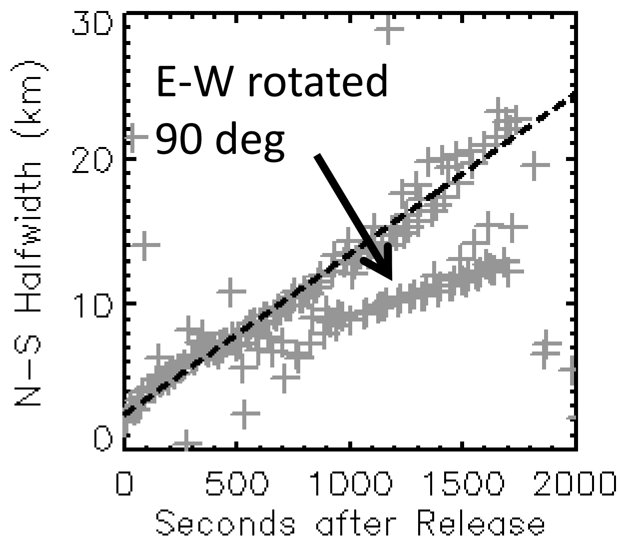


Cloud Width Fits

- **Data originally in pixel coordinates**
  - **Convert to km**
    - **Axes can be rotated relative to true N-S and E-W**
      - **"Tilt" paramater**
- **Rapid non-linear cloud expansion before 100 sec**
  - **Did not attempt to fit at these early times**
- **Very linear after 100 sec**
  - **E-W expansion greater for Launch 1**
  - **N-S expansion about 2x that of E-W for Launch 2**

Launch 2



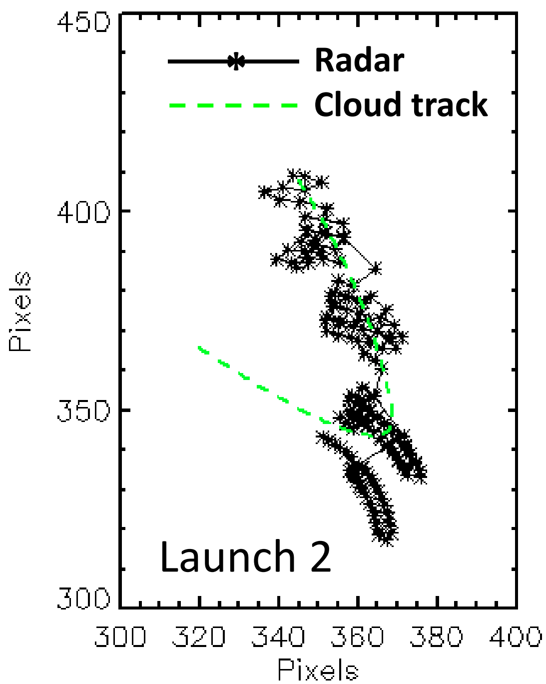


AFRL

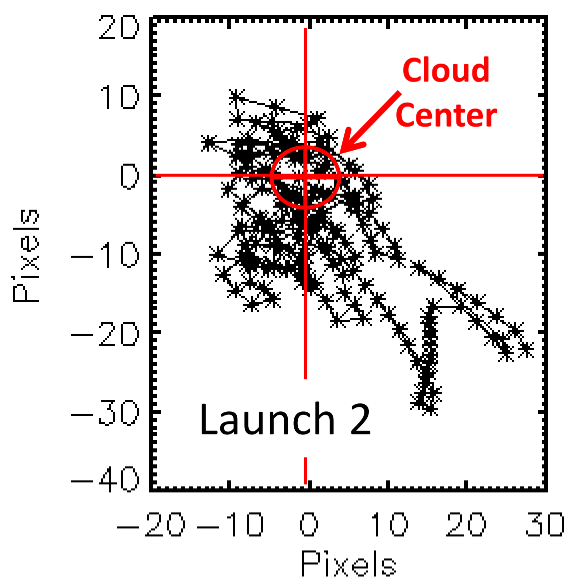
Relative Intensity Model

- **Absolute optical intensities not useful**
- **But relative intensities give cloud size and shape**
  - **Key to comparison with radar density data**
  - **Relative intensities for radar beam locations**
    - ***Now in coordinate system relative to cloud center!***

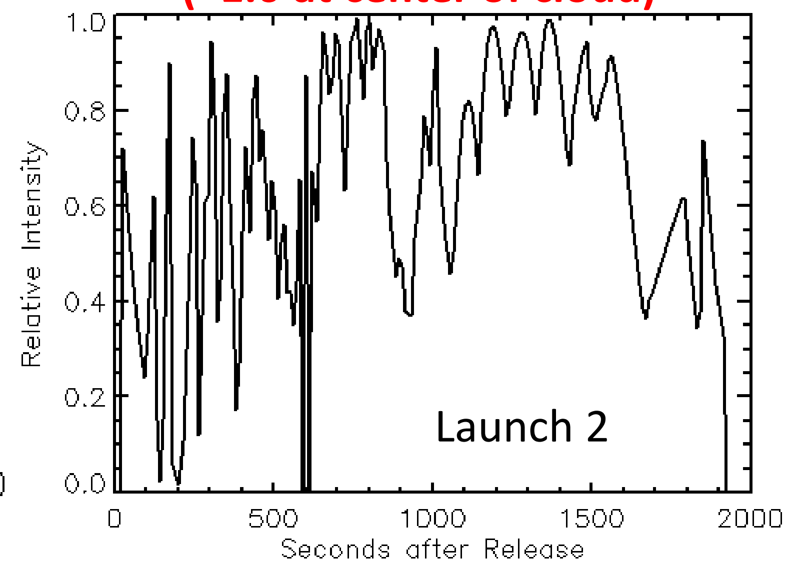
Radar pointing in image coords.



Radar pointing in cloud coords.

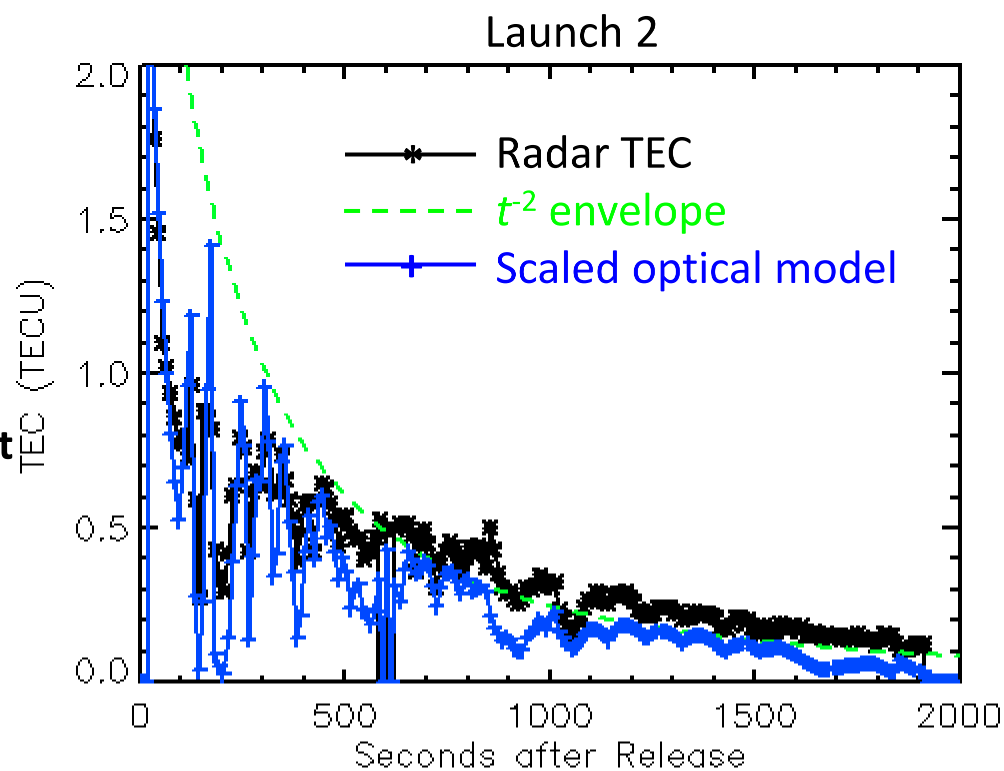


Relative intensity model
(=1.0 at center of cloud)



Comparison with Radar TEC

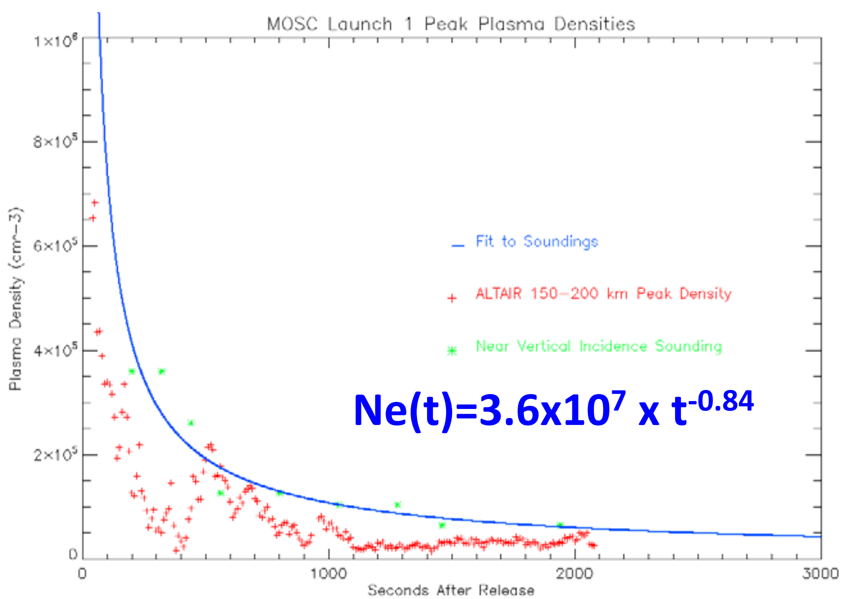
- **Raw radar data is function of range, az, el**
  - **Convert az and el to coordinates relative to cloud center**
- **Optical data is inherently integrated through the cloud**
  - **Near-vertical lines of sight**
  - **Integrate radar densities in range along beams to give closest equivalent to optical data (TEC)**
- **First-cut comparison:**
  - **Assume rapid ionization but small recombination**
    - **Total number of ions approximately constant after initial stages**
    - **Cloud expansion is dominant cause of density decrease**
  - **Observed linear expansion in 2-D (TEC) space should give t^{-2} dependence**
  - **Very good fit captures much of the structure**
  - **Individual fluctuations from scans across cloud clearly highly correlated**

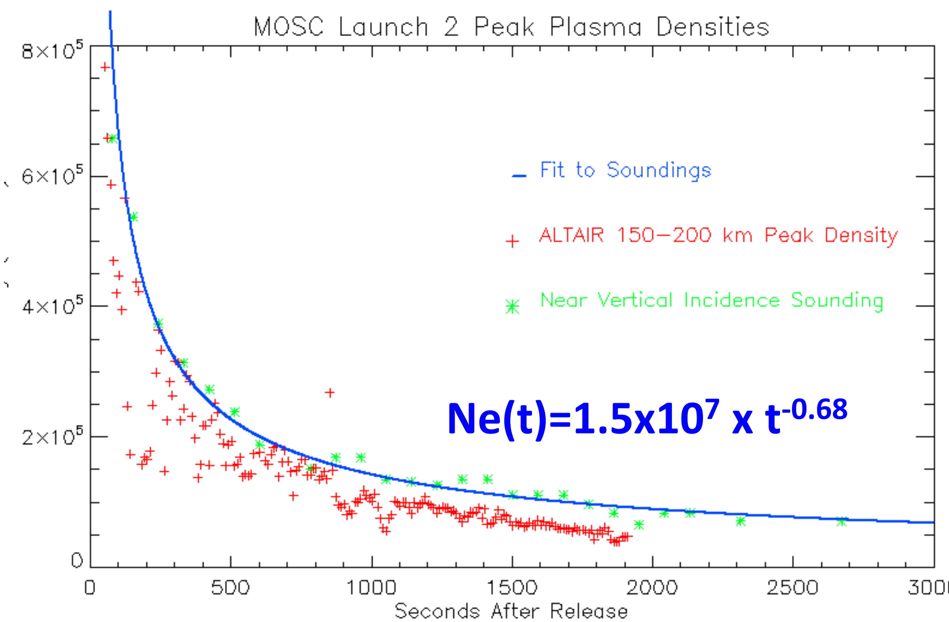


- **Reasonably good fit using only simple assumptions**
- **Optics clearly capturing cloud plasma structure**

Comparison with Overall Plasma Density Measurements

- Radar data represents minimum bound on peak cloud density
  - Only occasionally comes close to center of cloud
- Ionosonde picks up peak density regardless of cloud location
  - Should provide upper bound on radar measurements
- Log-log fit to sounder densities makes very nice upper bound on radar data for both launches
  - Exponents of ~-0.75 much smaller than -3 expected from constant particle number and 3-D linear expansion





Findings and Discussion

- **2-D Gaussian distribution a reasonable model for cloud size and shape**
  - **Overall good fits but misses some E-W asymmetry**
- **Cloud expansion very linear except at earliest times**
  - **Disagrees with theoretical diffusion-based prediction: $r \propto t^{\frac{1}{2}}$**
- **Optical model correlates well with radar TEC measurements: $TEC \propto t^{-2}$ gives reasonable scaling and fits well with linear expansion in 2-D**
- **Overall density dependence closer to $N_e \propto t^{-\frac{3}{4}}$**
  - **Why not $N_e \propto t^{-3}$ based on linear expansion in 3-D?**
    - **Ongoing electron production throughout experiment?**

Summary

- **Empirical model developed for MOSC Sm clouds**
  - **Position, size, and shape from optical fits to 2-D Gaussian**
  - **Density envelope from sounder and radar data**
- **Observed cloud expansion very linear with time**
  - **Constant number of electrons would give t^{-3} dependence**
- **Observed density drops off much more slowly than theory or fixed electron number would indicate: ~ $t^{-3/4}$**
  - **Ongoing ionization?**
- **Model already being used for high-fidelity raytracing to compare with RF observations**
- **Planning to use as input to background dynamics model to examine impact on Rayleigh-Taylor instability**

Contours of Half-Maximum N_e for Launch 2