

Status of the Rotating Electric Field Ion Mass Spectrograph (REFIMS) and Its Use in the Space Environment

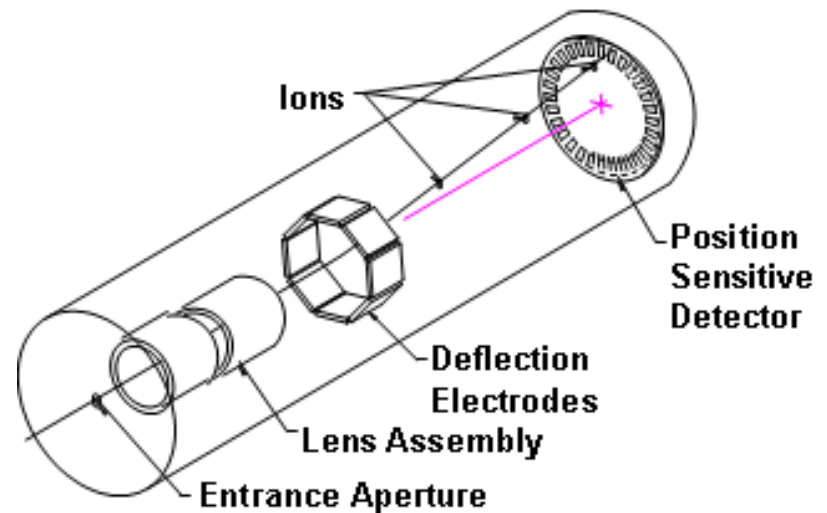
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The REFIMS Idea

- The REFIMS idea began by thinking of new ways to perform time-of-flight (TOF) spectrometry
- The basic idea was to replace the “start pulse” of a modern TOF system with an electric gate
- It was quickly realized that a straightforward gating scheme requires the gate to be “off” much longer than it is “on,” so the scheme suffers from having a poor duty factor
- The way around the duty factor problem was to utilize a set of flight paths that the beam would be steered to
 - Following the closing of the electric gate for one flight path, the beam is steered to the next path, then the gate is opened
 - Each flight path has its own “stop” detector



- The complete REFIMS idea converts this sequence of discrete steps to an “analog” representation
 - The gating and steering functions are performed by a single harmonic electric field
 - The multiple flight paths become a continuous blend
 - The individual “stop” detectors become a position-sensitive array

The REFIMS technique can be thought of as a time-of-flight variant



Significant REFIMS Milestones

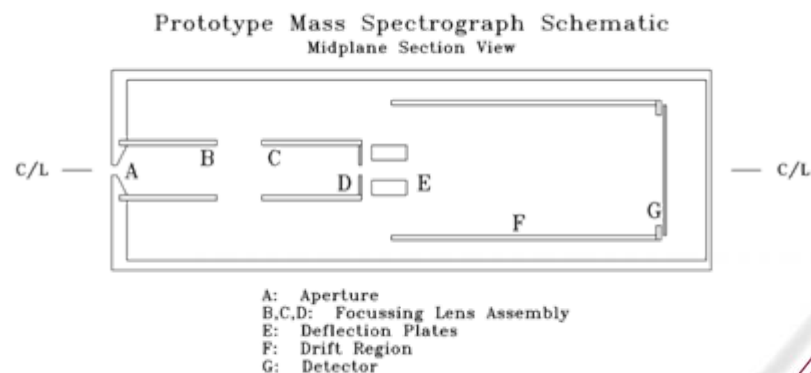
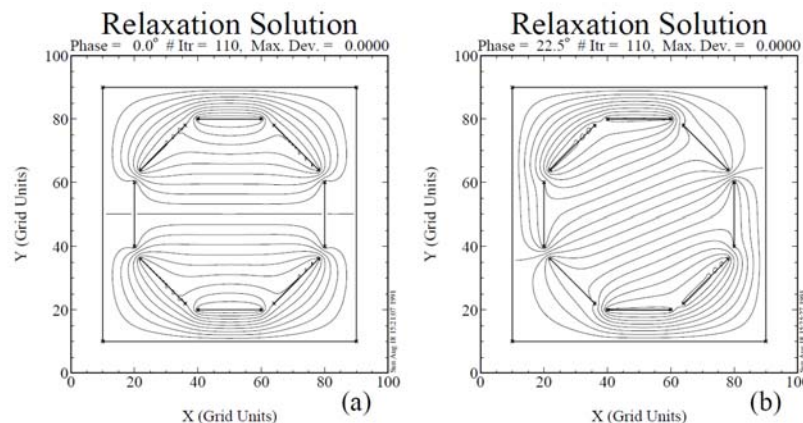
- 1985 – Idea conceived and prototyped
- 1992 – Idea and prototype results published in Ph.D. dissertation
- 1996 – Further analytical study performed
- 1998 – Published in open literature
- 1998 – Worked with others on mass filter variant
- 1999 – Performed simulation work to improve resolution
- 2001 – Resumed prototyping work
- 2002 – Began development of protoflight instrument for ionosphere
- 2007 – Flew protoflight instrument on sounding rocket
- 2009 – Began development of new instrument for sounding rocket

As a “new” idea, REFIMS has seen low-level effort for a quarter century



Early REFIMS Prototype

- The first REFIMS work was performed in the 1980s as documented by *Clemmons* [1992].
- A uniform electric field that rotated in time was desired, and computer simulations using a home-built code showed that phased sinusoids placed on an array of eight electrodes would produce the desired field
- A simple electronics design was employed to synthesize the sinusoidal signals
 - *A tank LC circuit was used*
 - *The tank circuit was stimulated by digital signals to provide proper phasing and to allow digital timing*
- The detection scheme was based on a microchannel plate detector with a resistive anode encoder read out by a Surface Sciences (now Quantar) 2-D imaging system
 - *The readout system included custom electronics that interfaced to a multichannel analyzer to provide histogrammed timing locked to the frequency of the field synthesizer*
- A prototype instrument was drawn up based on “pencil-and-paper” approximations and fabricated

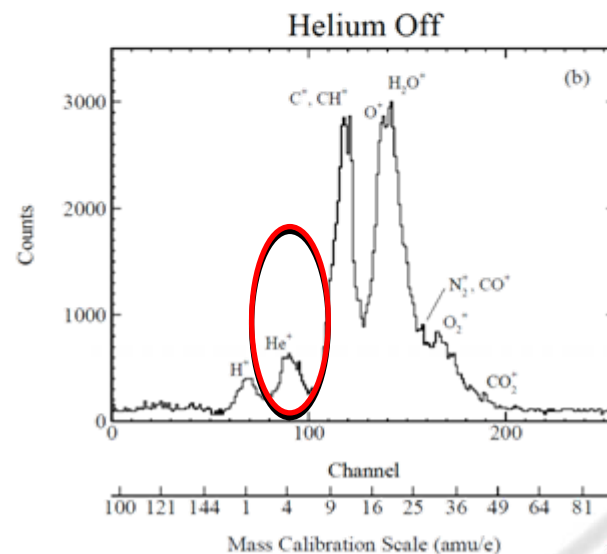
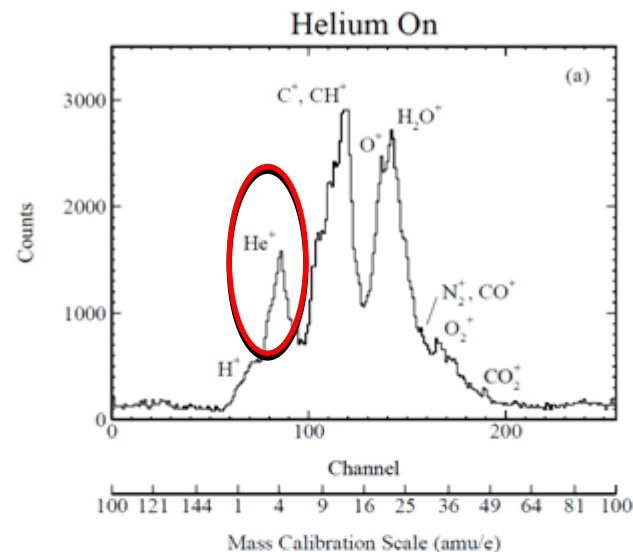


Early work included computer calculations and prototype hardware



Early REFIMS Prototype Results

- The REFIMS prototype was tested in a diffusion-pumped vacuum chamber
- A simple ion source fed by residual chamber gas was used to stimulate the instrument
- A leak valve was used to admit helium into the chamber
- Mass peaks were recorded
 - *Dispersed by mass^{1/2} (see equations below) as expected for time-of-flight system*
 - *Peaks were broad, probably due to unoptimized ion optics*



Crude mass resolution was achieved with the first REFIMS prototype



REFIMS Principles of Operation

- REFIMS principles have been put forward in the literature by *Clemmons and Herrero* [1998].
- Based on analytical work using the parameters defined in the schematic at the right
- An ideal uniform field directed transverse to the axis rotating at an angular frequency of ω is assumed
- Timing for the time-of-flight (TOF) measurement is done when a particle is detected
 - “Stop” time is determined in a straightforward manner
 - “Start” time is inferred from the azimuthal position of detection
 - In practice, TOF is reported as an angular displacement by relating through the angular frequency, ω
- The paper discusses several variants of the technique that utilize various ranges of instrument design parameters

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Mass spectroscopy using a rotating electric field

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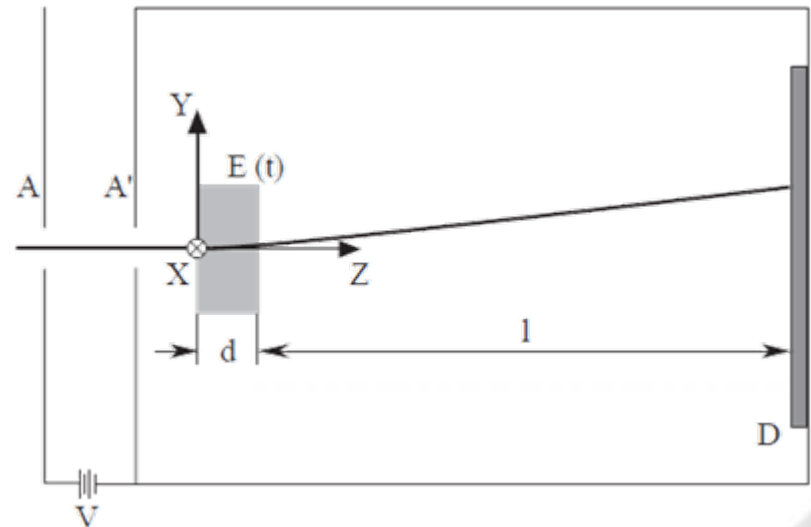
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(Received 4 December 1997; accepted for publication 27 March 1998)

A mass spectrograph using a rotating electric field and position-sensitive detection is described. Its principles of operation are explained, and a prototype instrument and its test results are presented and discussed. Examination of how the instrument's properties vary under changes of its parameters (e.g., geometry) shows how it can be tailored to specific measurement requirements. The general case utilizing detection in two (polar) dimensions is discussed, and limiting cases employing one-dimensional imaging in each direction, azimuthal and radial, are presented. Applications are suggested and courses for further development are put forth. © 1998 American Institute of Physics. [S0034-6748(98)04206-3]



REFIMS principles have been put forth in the literature



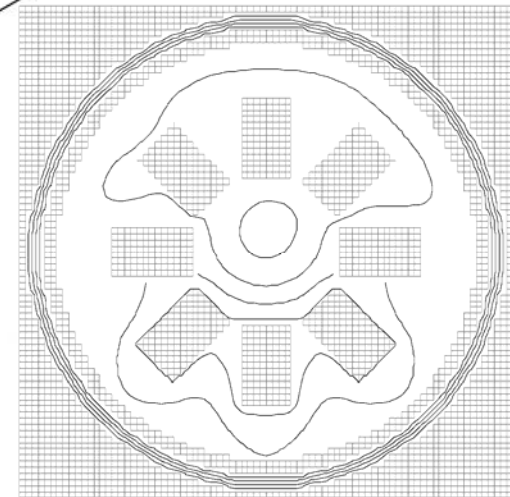
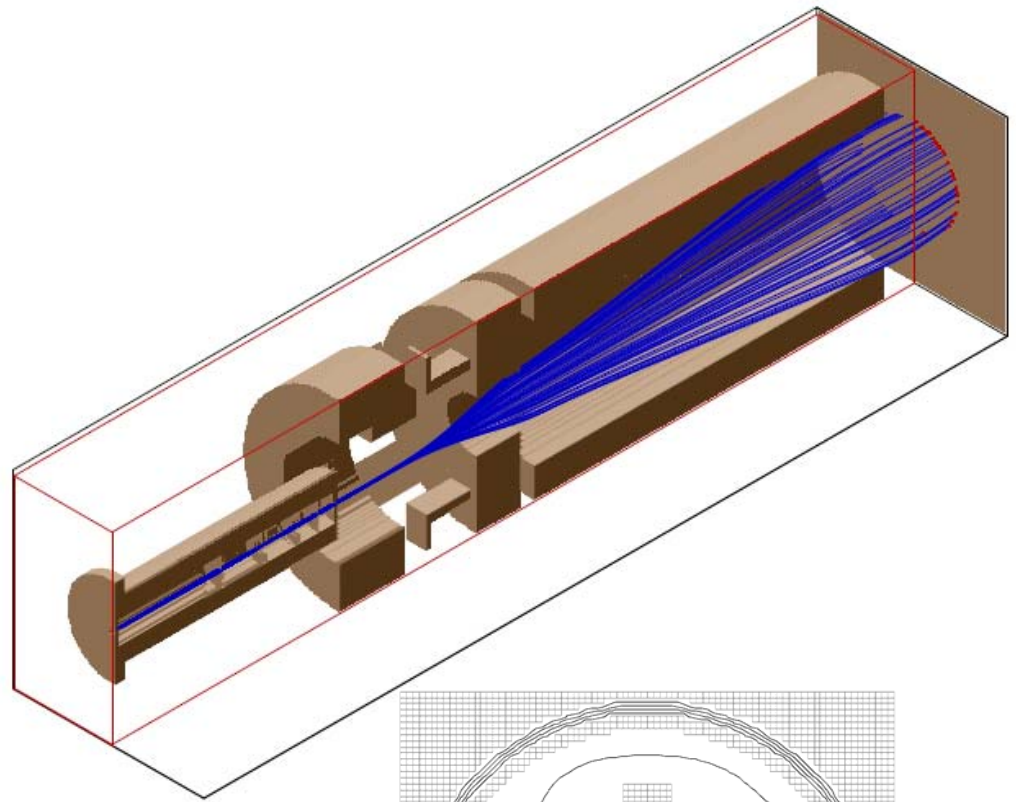
REFIMS Prototype Determination of Mass

- Position-sensitive detector gives particle position (r , Θ) and detection time (τ)
- Detection time is used to look up phase of rotating field, Φ
- De-rotated angular position, α , constructed using
$$\alpha = \Theta - \Phi$$
- De-rotated position related to ion mass, m :
$$\alpha \sim m^{1/2}$$
- Constant of proportionality depends on geometry and rotation frequency
 - *See paper mentioned above for more details*



Design Refinement thro

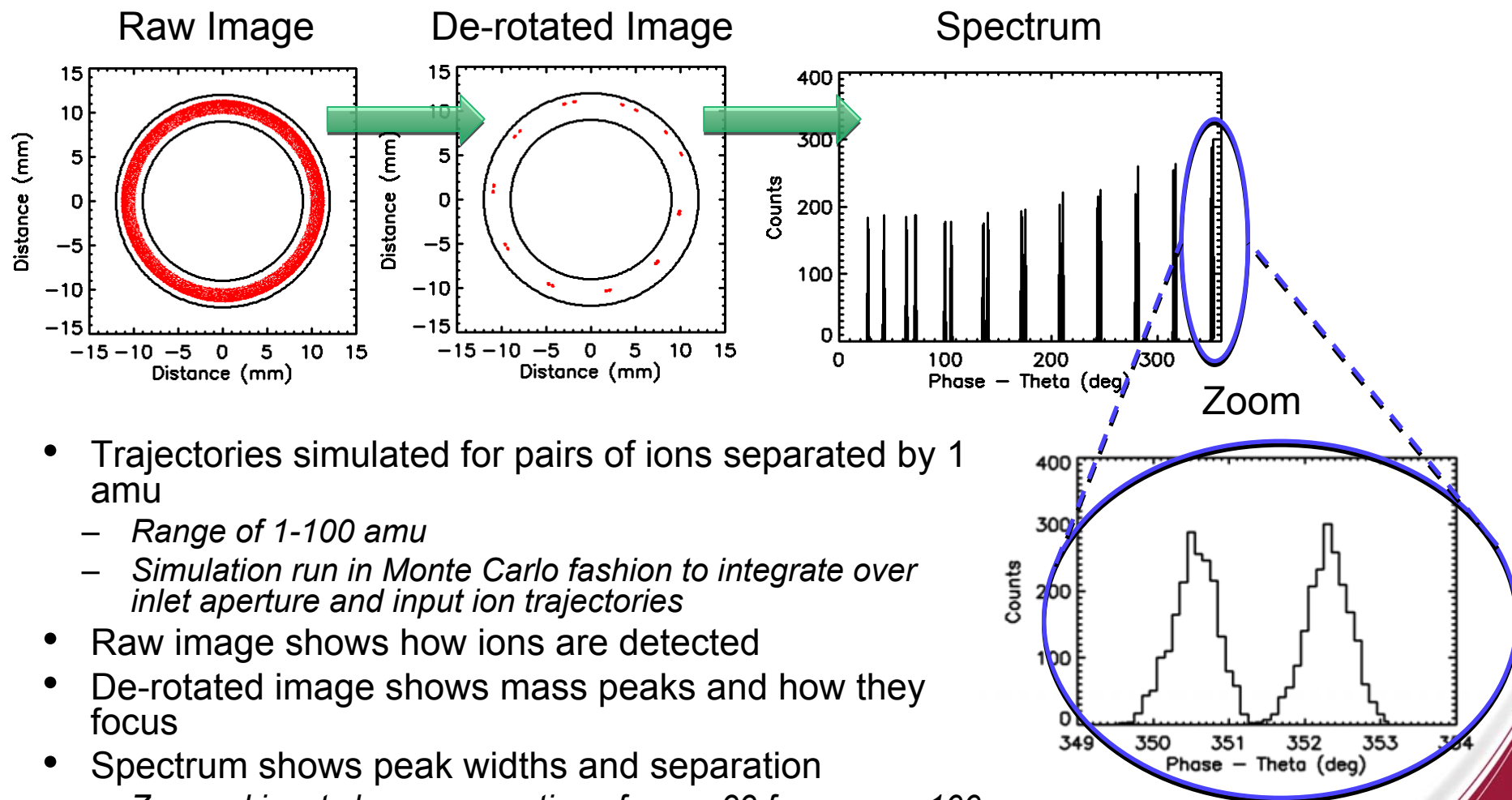
- Computer simulations using the SIMION software package have been used to refine the prototype design
 - *Improving the focusing was a primary goal*
- A large post-acceleration placed after the deflection region helped focusing
 - *The deflection field no longer looks uniform due to leakage, but the effect is to improve the focus*
- Other electrodes were used to improve focus



Modern computer simulation tools allow rapid design refinement



Simulation Results



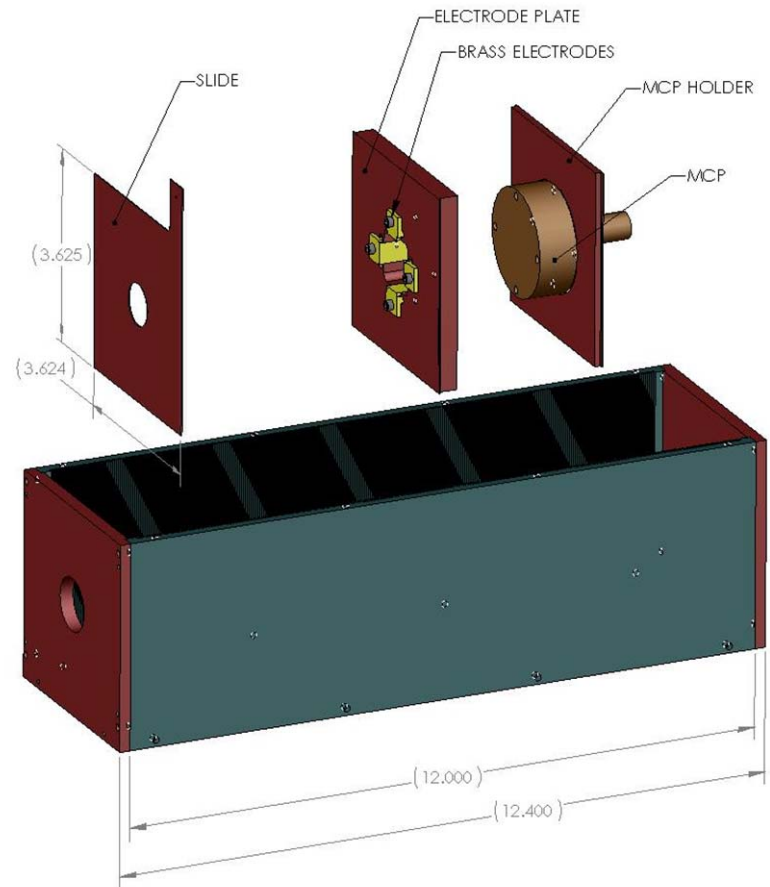
- Trajectories simulated for pairs of ions separated by 1 amu
 - Range of 1-100 amu
 - Simulation run in Monte Carlo fashion to integrate over inlet aperture and input ion trajectories
- Raw image shows how ions are detected
- De-rotated image shows mass peaks and how they focus
- Spectrum shows peak widths and separation
 - Zoomed inset shows separation of mass 99 from mass 100

Simulations show that REFIMS can resolve masses with $m/\Delta m$ of 100



Prototyping System

- To explore the system further, a prototyping system was developed based on the simulations
- A four-electrode deflection system was used to simplify the electronics
 - *Two RF amplifiers were used to drive the deflection electrodes*
 - *The amplifiers were driven by two phase-locked channels of a four-channel signal generator*
- Cylindrical lenses were effected with a series of slats having a variety of hole sizes
 - *Static adjustable power supplies allowed the lens potentials to be adjusted*
- A 25-mm microchannel plate with resistive anode encoder was used as a detector
 - *A Quantar readout system was used to measure ion landing time and position*
- A PC containing data acquisition cards from National Instruments was used to collect data from the Quantar and to interface to the signal generator
 - *Labview-based software controlled the system and acquired, processed, and displayed the data*

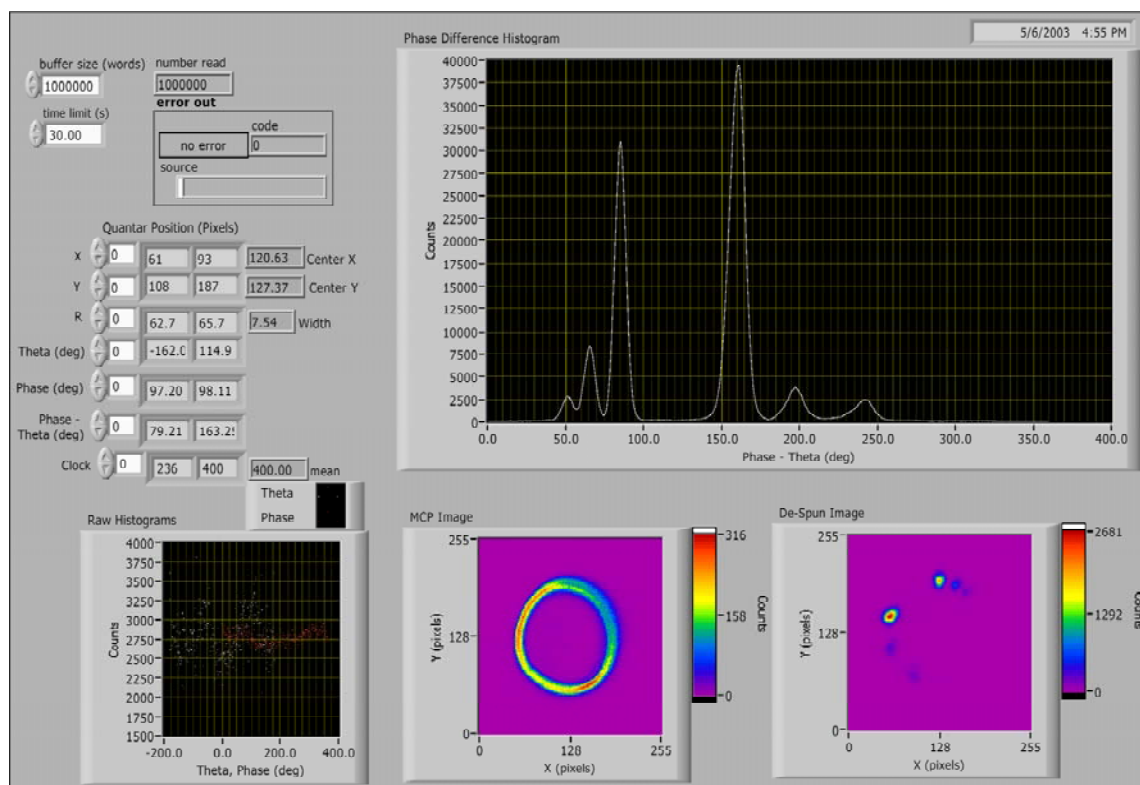


A flexible prototyping system allowed rapid changes in geometry and other parameters



Results from Tests using Prototyping System

- Shown is a screen print from tests of the prototyping system
- Residual chamber gas used with Kimball Physics ion source
- Mass peaks are clear

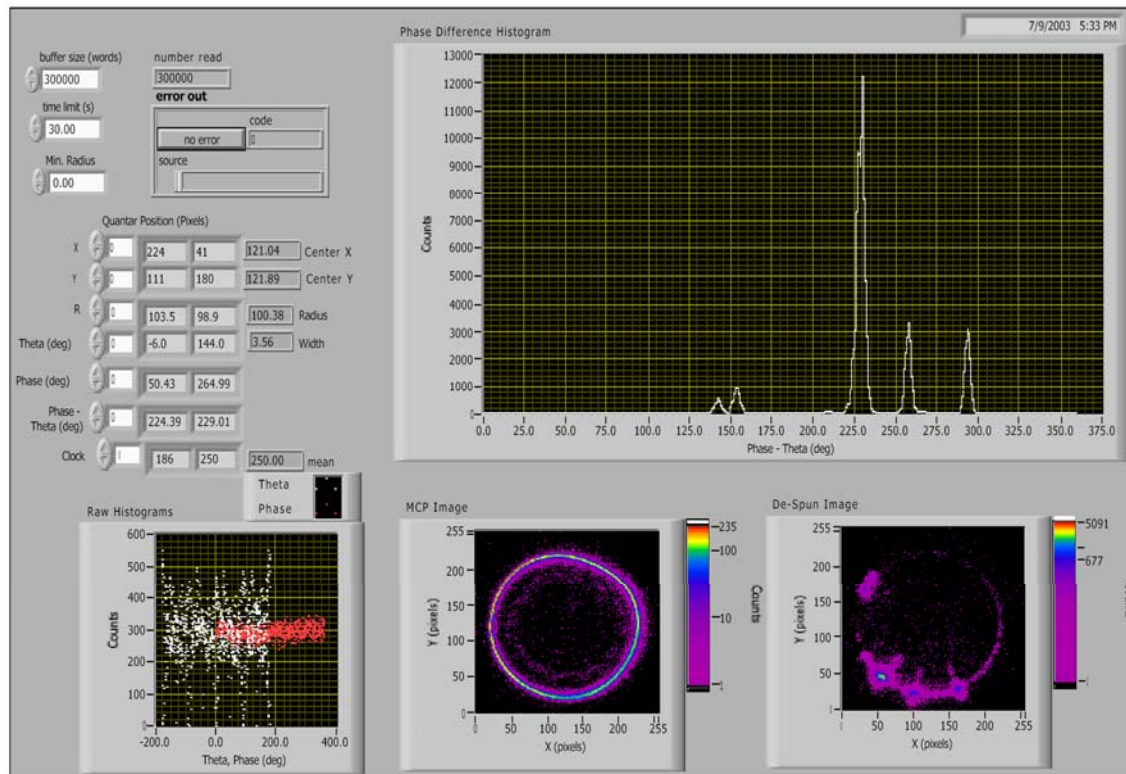


Prototyping system was an effective development tool



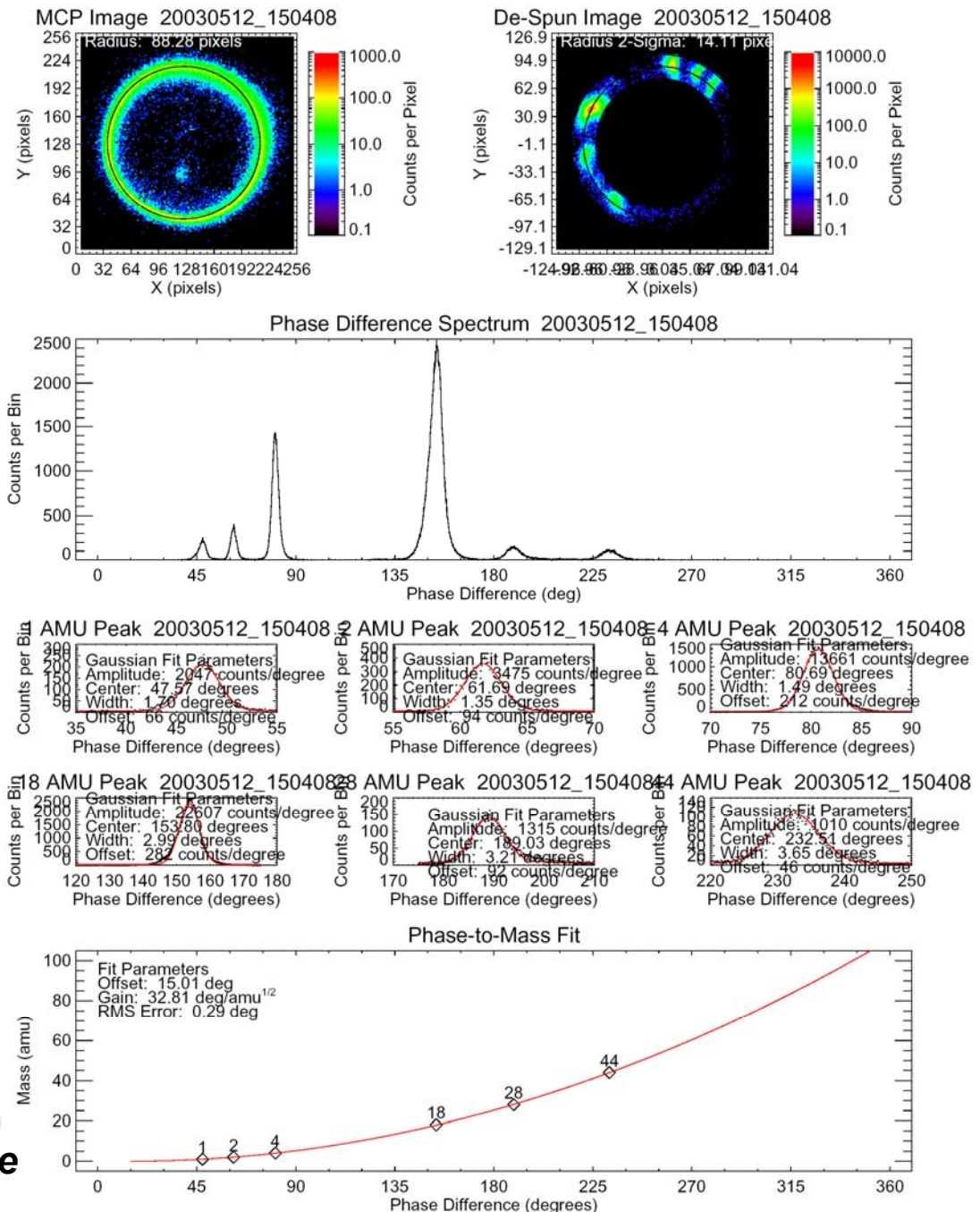
Refinement using Prototyping System

- In order to sharpen peaks, a smaller aperture was employed
- An energy filter also was added to make input beam more monoenergetic
- Improved peaks resulted



Processed Results

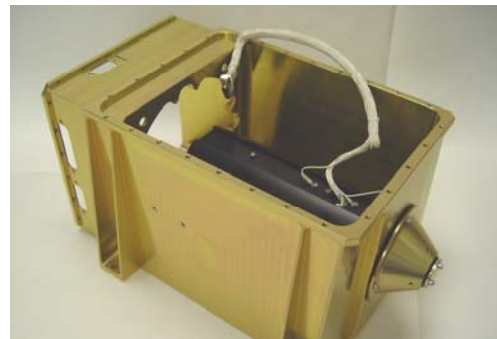
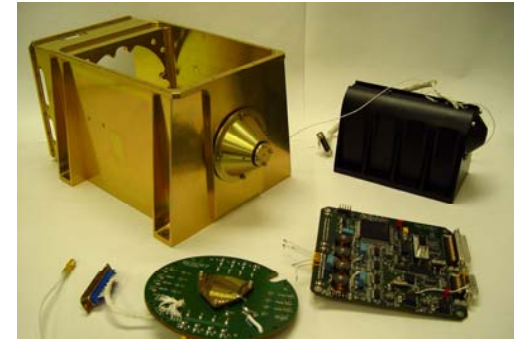
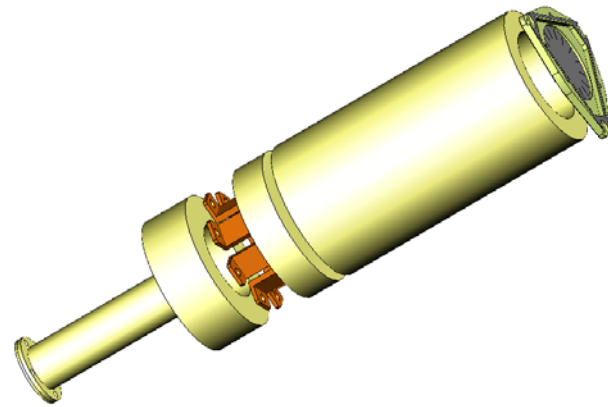
- Data collected from the prototyping system were analyzed to look at response in detail
- The data were centroided to ensure that the azimuthal angle was measured as accurately as possible
- Data more than two σ away from the image ring were discarded
- Peaks in spectrum were least-squares fitted with a gaussian
- Peak widths corresponded well with values expected using standard error propagation techniques
 - Widths were in the 1-4 degree range
- Peak positions were fitted to analytical formula and found to fit well within expected errors
 - RMS error of 0.29 deg
 - Gain of about $33 \text{ deg/amu}^{1/2}$



Analysis shows that actual response is well-described by theory

Protoflight Design

- Once satisfactory performance was achieved, the next step along the development path was to work toward a spaceflight version
- Previous prototypes relied on laboratory equipment that cannot be flown, so the goal was to develop a system that could perform as a standalone unit, requiring only power, telemetry, and possibly simple commands
- A suborbital flight into the ionosphere was available for testing purposes, so a protoflight unit was designed and fabricated based on the parameters derived from previous work



The protoflight design was based on parameters from earlier prototypes



Protoflight Design

- The protoflight unit utilized eight electrodes to create the deflection field
- The deflection field driver had an amplitude of 70 V and ran at 250 kHz
 - *For this geometry, mass range was about 1-80 amu*
- The detector utilized a 25-mm microchannel plate (MCP)
 - *Rather than a full imaging readout, position sensitivity was produced using a mask over the MCP having 16 slits for particles to pass*
 - *Each slit illuminated a portion of the MCP in front of a metallic anode, which was read out using an Amptek A121 preamp*
- Custom electronics controlled the deflection field, read out the 16 A121s, performed the necessary image de-rotation, and histogrammed the resulting data
 - *Counts were accumulated in two banks of histogram memory, each having 512 angular channels (about 0.7 deg resolution)*
- Potentials for static electrodes and the MCP detector were created using Emco high voltage supplies
- Spectra were accumulated for 16 ms before being sent to the rocket's telemetry system through an RS-422 link

The protoflight design was based on parameters from earlier prototypes



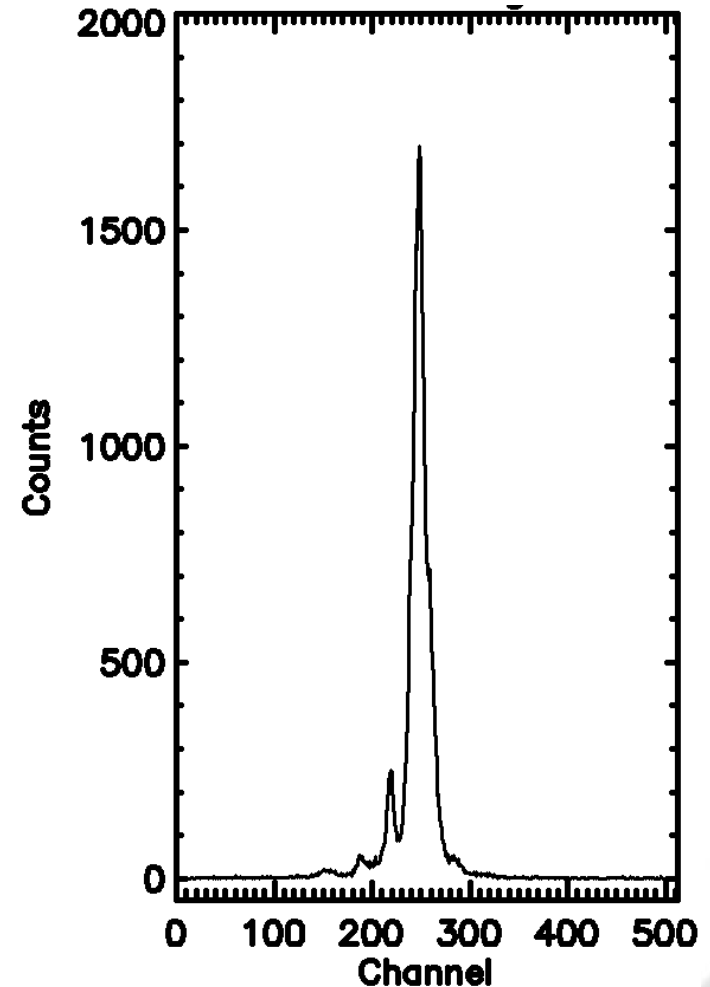
Testing of Protoflight Unit

- The protoflight unit was tested in a vacuum chamber pumped with a turbo pump to about $1\text{e-}6$ torr
- The ion source used was a Colutron ion gun having the capability to provide flux at energies of 0.1 eV
- The gun uses a plasma discharge source into which gas mixtures are admitted
- A Wien velocity filter can be used to select a given ion species
- The rocket telemetry was simulated using a National Instruments card in a PC and data were acquired and displayed using Labview-based software



Protoflight Test Results

- An example spectrum from the protoflight testing is shown on the right
- Argon gas was used in the Colutron gun
- The velocity filter was not used, thus the extra mass peaks
- Although the mass resolution was not as good as hoped, it was adequate for most purposes in the ionosphere



The protoflight unit exhibited reasonable performance on the ground



Sounding Rocket Flight Results

- The protoflight unit was launched in December, 2007 from Andoya Rocket Range in Norway
- The rocket experienced a severe failure of a major portion of its telemetry system shortly after launch, so no useful ion spectra were received from the REFIMS instrument onboard
- The “housekeeping” data received before the failure showed that the instrument was working nominally at the time of telemetry failure



No useful ion spectra were obtained during the flight test



Future directions for REFIMS

- A new NASA grant to fly REFIMS on a pair of sounding rockets in Summer, 2011 has been received
- The mission concentrates on relatively low-altitude phenomena, so a miniature turbo pump will be incorporated into the design to maximize data return
- Work is being performed to improve the instrument performance
 - *Simulations to improve focusing, thus allowing a large aperture*
 - *Improvements in electronics are under way*
- Other work is underway to develop a 1-D azimuthal imaging readout for the MCP readout
 - *A time-delay anode is the current architecture*
- *Space News* recently published a news article reporting on NASA's award of an instrument based on REFIMS technology to fly on the European Bepi-Colombo mission to the planet Mercury

More work remains to demonstrate that the REFIMS concept can produce science-quality data

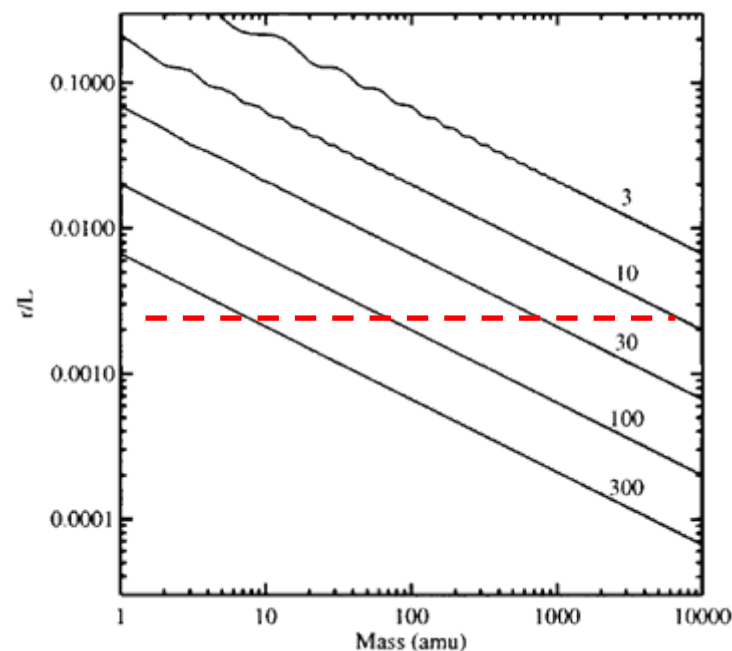


REFIMS Operation as a Mass Filter



Radial Imaging

- As discussed by *Clemmons and Herrero* [1998], other variants on the REFIMS principle can also yield mass information
- One such idea is to increase the rotation rate of the field such that particles no longer feel an impulse, but rather are influenced by the field for many rotations
- In this realm, masses can be imaged radially
- A mass filter can be constructed by having a single (non-imaging) detector at a given radius, then sweeping the frequency of the deflection field
- Hardware based on this variant was developed and tested by S. Smith at JPL in the 1990s
- We developed further theory on this variant while working with S. Smith
- To our knowledge, this variant has fallen into disuse and has not been developed further recently, although the idea still has merit



A REFIMS-based mass filter can be based on a swept frequency deflection field

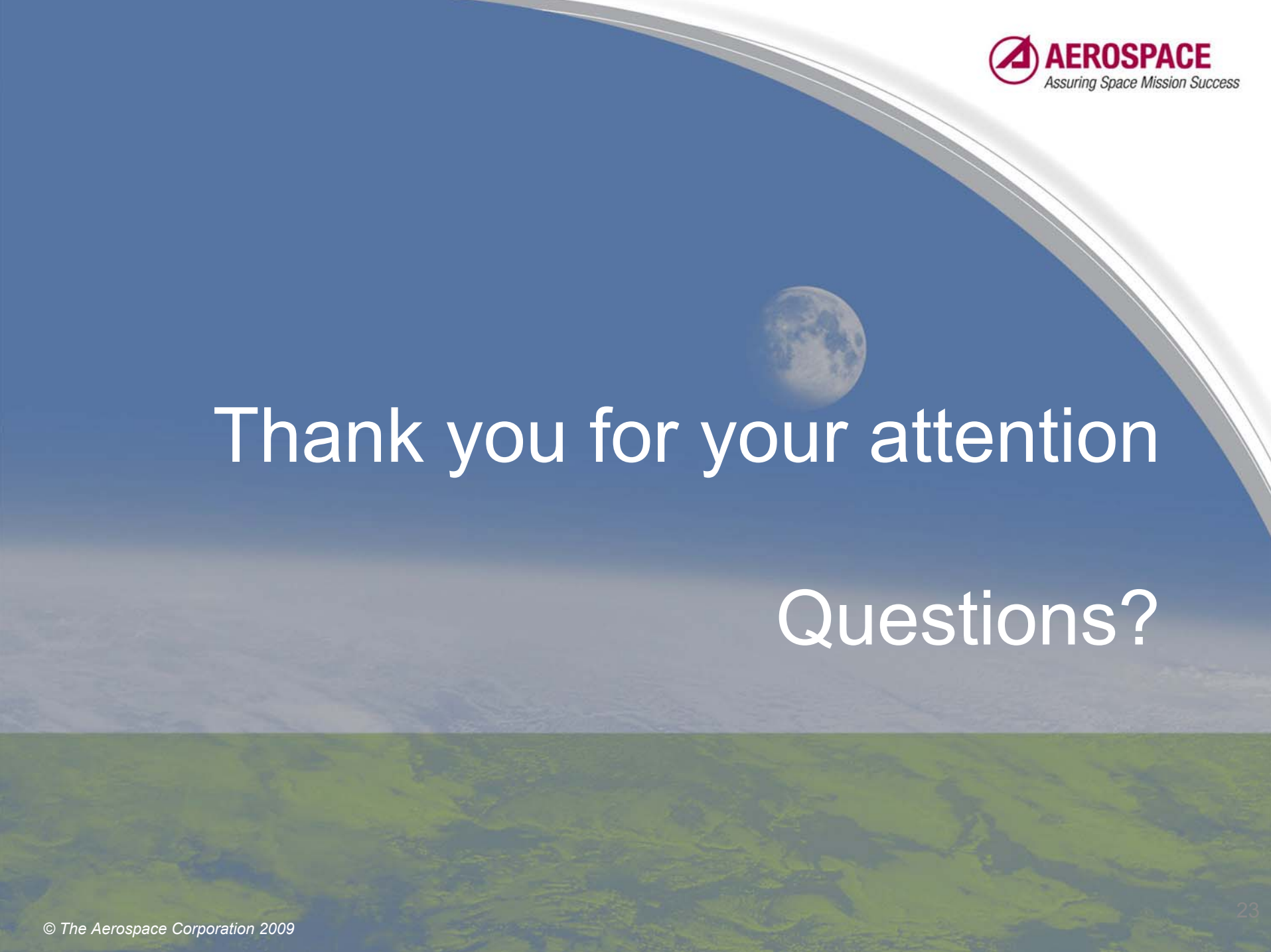


Conclusion

- The REFIMS idea and its principles have been put forth and discussed
- The development path at UC Berkeley and Aerospace has been shown
- The current status of the REFIMS technique is that it has approached true usefulness
- Another flight attempt is on the horizon
- New developments are being employed to improve the instrument's performance
- Apparently others have advanced the technique to the point of usefulness in space
- Other variants of the REFIMS principles still hold unevaluated promise

REFIMS will soon be proven as a technique for fast, moderate-resolution mass spectrometry





Thank you for your attention

Questions?