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Title: The ChemCam Laser-Induced Breakdown Spectroscopy (LIBS) Instrument on the Mars Rover Curiosity

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November 15, 2011

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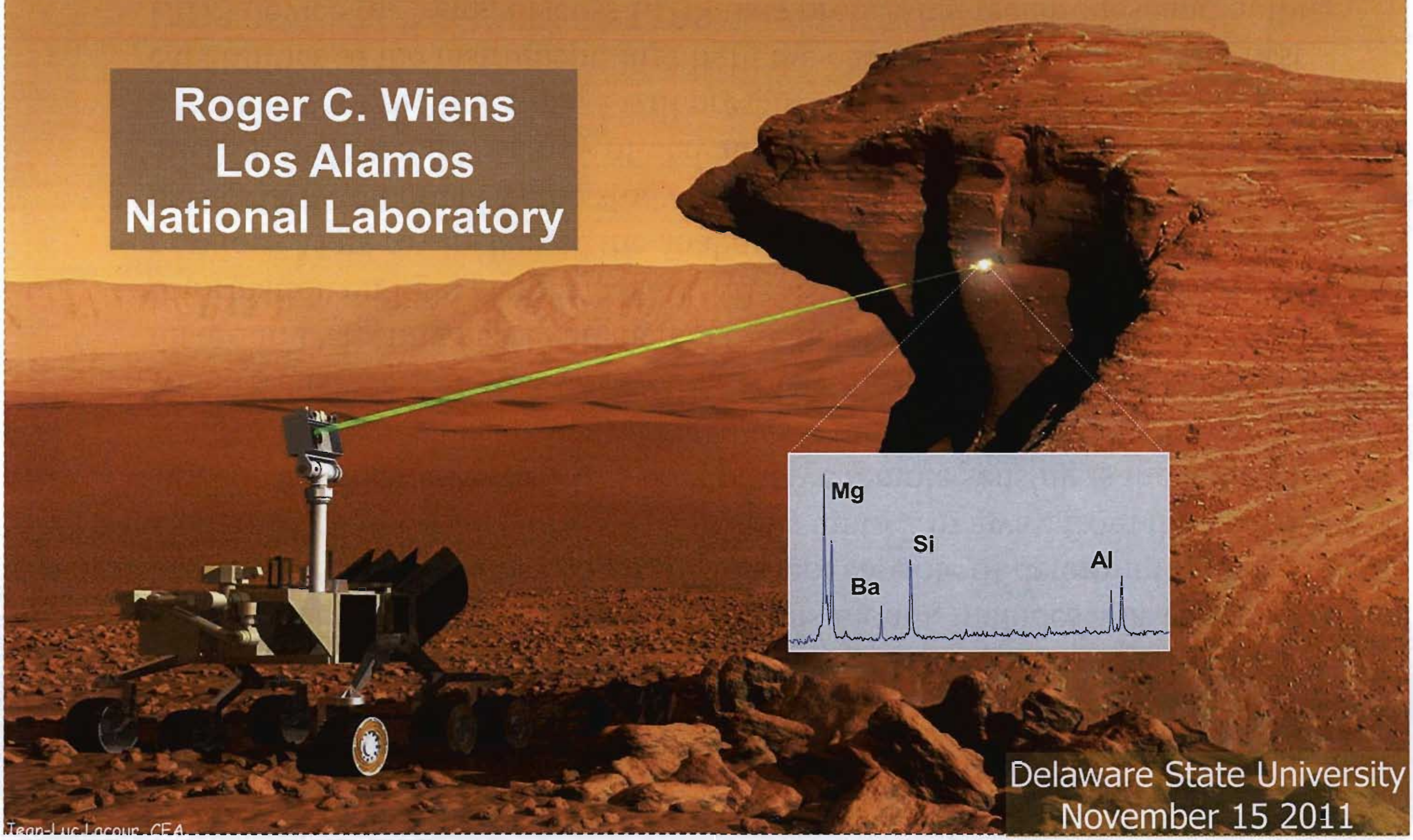
The ChemCam Laser-Induced Breakdown Spectroscopy (LIBS) Instrument on the Mars Rover Curiosity

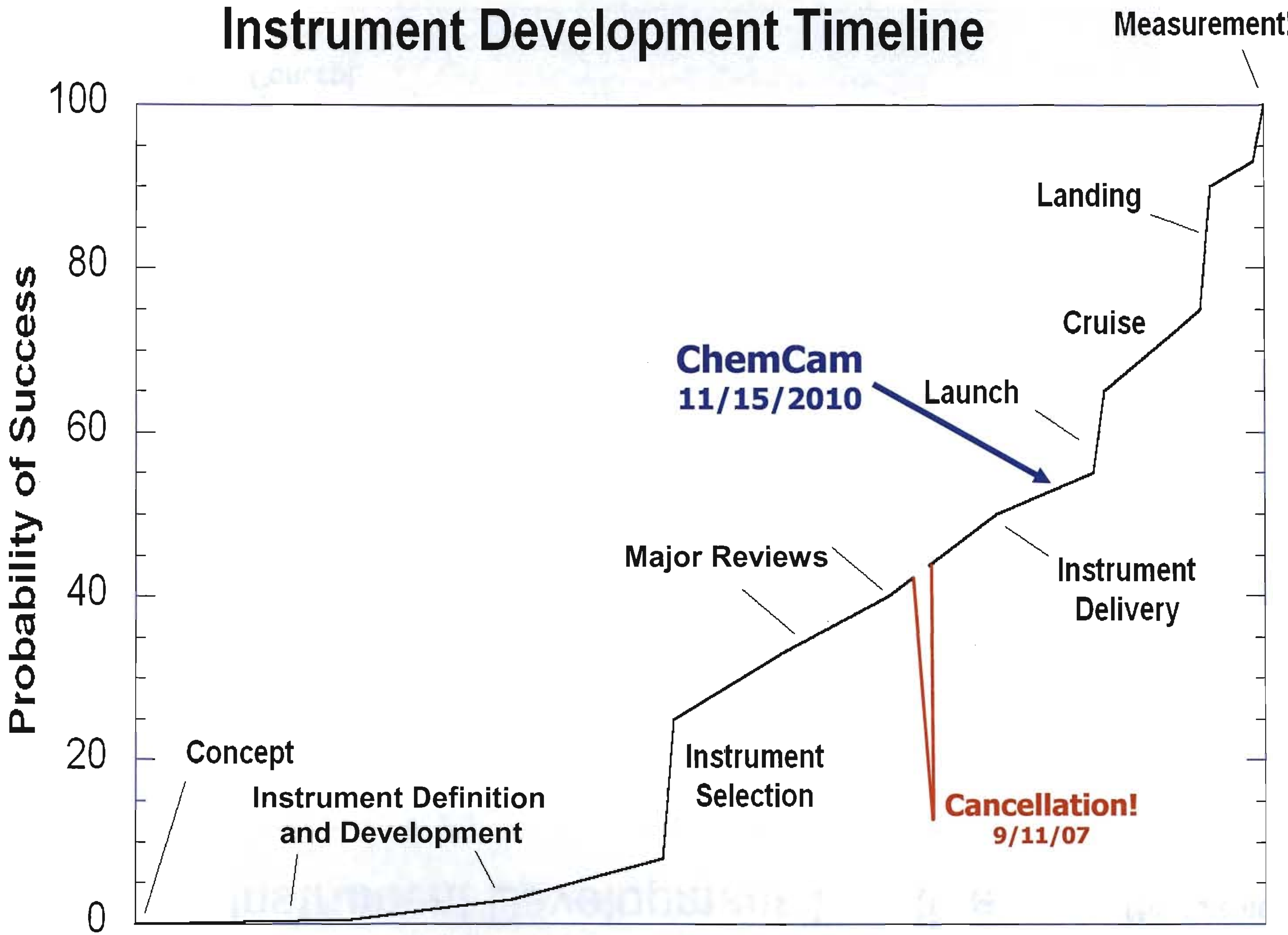
Roger C. Wiens
Los Alamos National Laboratory



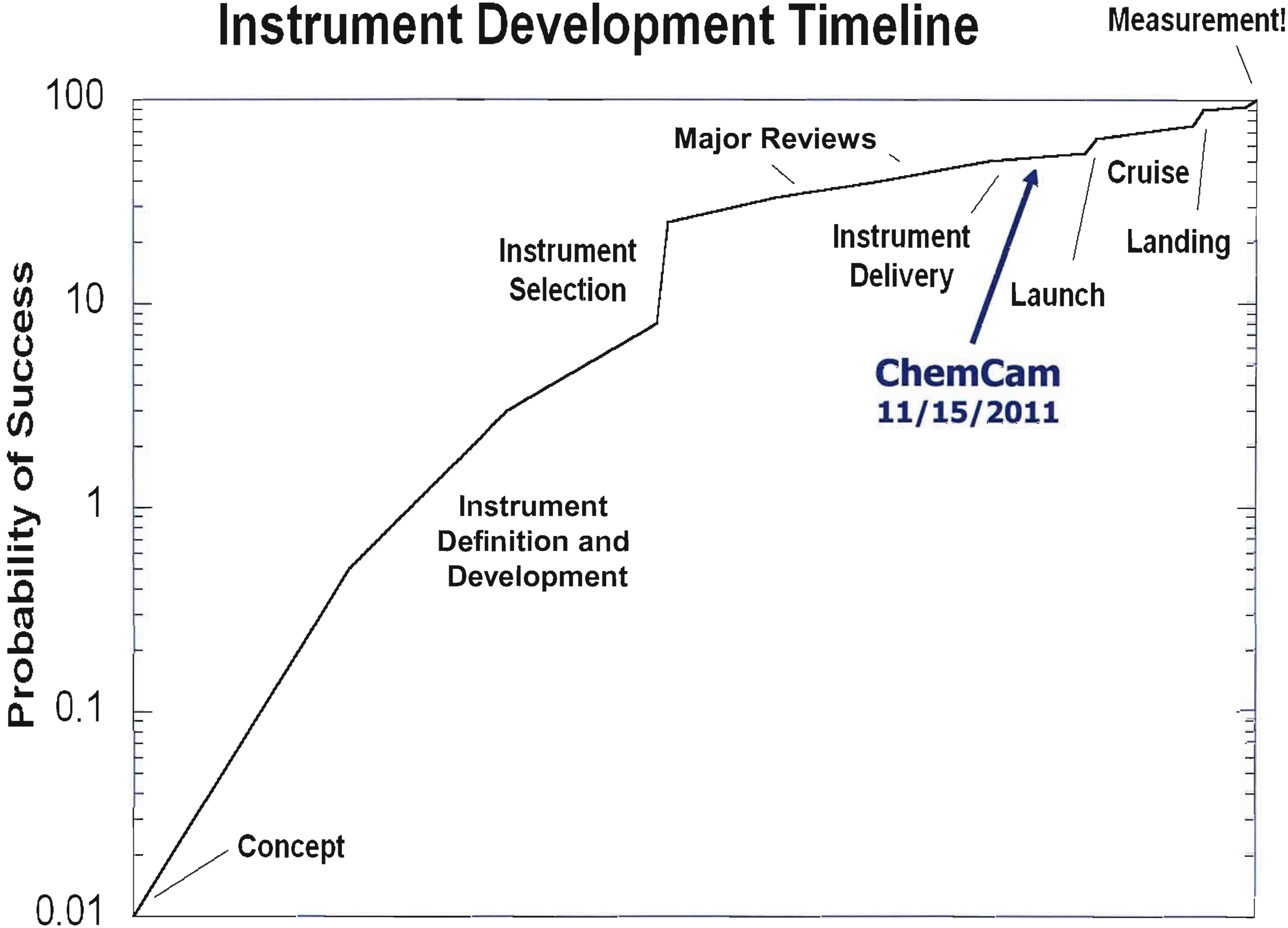
Delaware State University
November 15 2011

Abstract

- NASA's newest Mars rover, launching this month, includes a laser-induced breakdown spectroscopy (LIBS) instrument capable of determining the elemental compositions of rocks and soils up to 7 m away from the vehicle. A significant advantage for LIBS over passive remote sensing is the ability to remove obscuring dust using repeated laser pulses. Similarly, LIBS can study weathering layers on rocks as well as ablate through to analyze the underlying material. Detecting nearly all elements, ChemCam LIBS will provide the first information on light elements, H, Li, Be, B, C, N, and O, for which the previous Mars rovers lacked the analytical capability. These elements are particularly important in the study of Mars habitability—the goal of this mission—allowing the study of clay minerals and searching for nitrates and carbonates for the first time. I will present the goals of this venture and capabilities of the instrument, highlight the challenges of building the first LIBS device for Mars, discuss LIBS data processing techniques, and outline our operation plans.


Instrument Development Timeline
Measurement!
100
80
60
40
20
0
Probability of Success
Landing
Cruise
ChemCam
11/15/2010
Launch
Major Reviews
Instrument
Delivery
Concept
Instrument Definition
and Development
Instrument
Selection
Cancellation!
9/11/07

Instrument Development Timeline



Collaborators

- Dr. Sam Clegg
  - Director of LIBS lab at LANL
  - Instrument Lead for Venus project
- Dr. Jeremie Lasue
  - Postdoctoral Researcher at LANL
  - Expert in Statistical Analysis
- Dr. Sylvestre Maurice
  - ChemCam Deputy PI, Lead in France

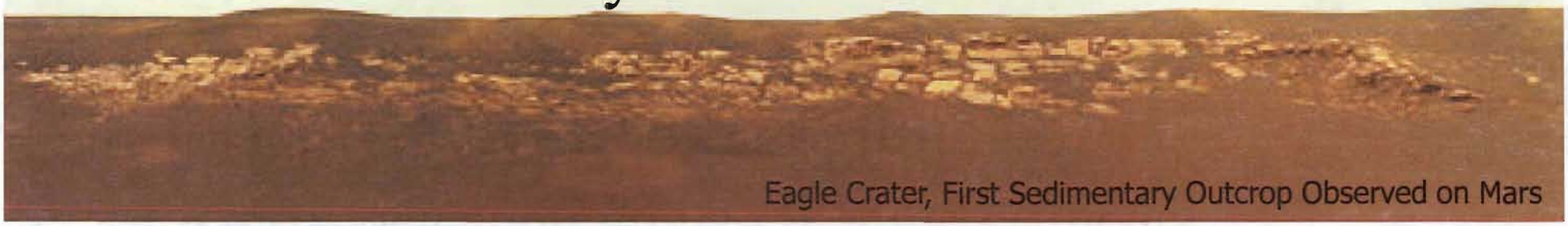
NASA/JPL/Cornell

Outline

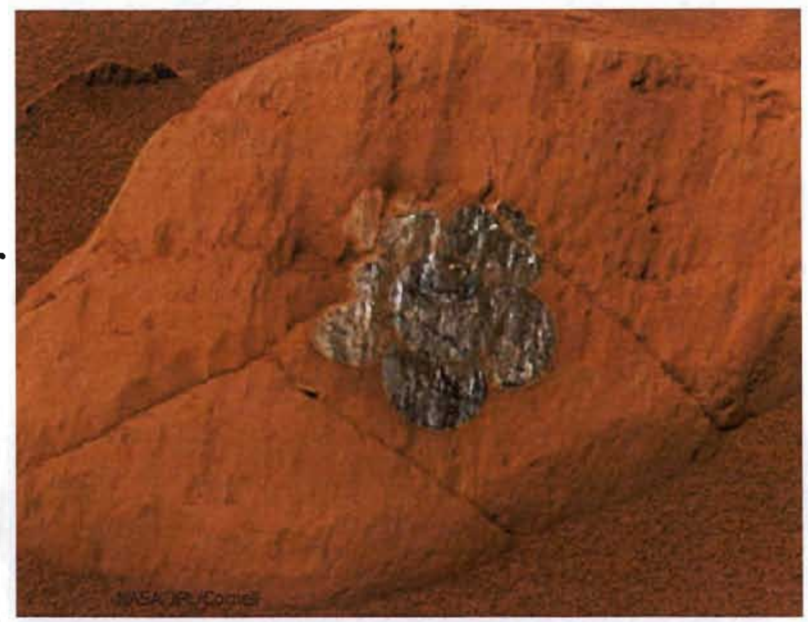
- What is LIBS?
- Why is LIBS needed on Mars?
- Instrument Requirements
- ChemCam
- Data and Operations
- Future applications
  - Venus Lander
  - Lunar & Asteroidal Environments

NASA/JPL/Cornell

Why LIBS on Mars?


Eagle Crater, First Sedimentary Outcrop Observed on Mars

- Mars is a Difficult Place For Remote Sensing
  - Surfaces Typically Covered by Dust and/or Weathering Coatings
  - Active Remote Sensing Much Better Than Passive Under These Circumstances
    - Eagle Crater Sedimentary Rocks Not Initially Identified by Remote Sensing on the Opportunity Rover
    - Most Samples Had to Be Brushed Off Before Identification



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LIBS Advantages

- No sample preparation required
- Rapid analysis technique
- Operates at a distance (ChemCam: 1.5-7 m)
- Removes dust from surfaces
- Provides depth profiles
- Detects nearly all elements
  - Includes H, Li, Be, B, C, N, O
  - Low detection limits for some elements
- Laser requires relatively little power

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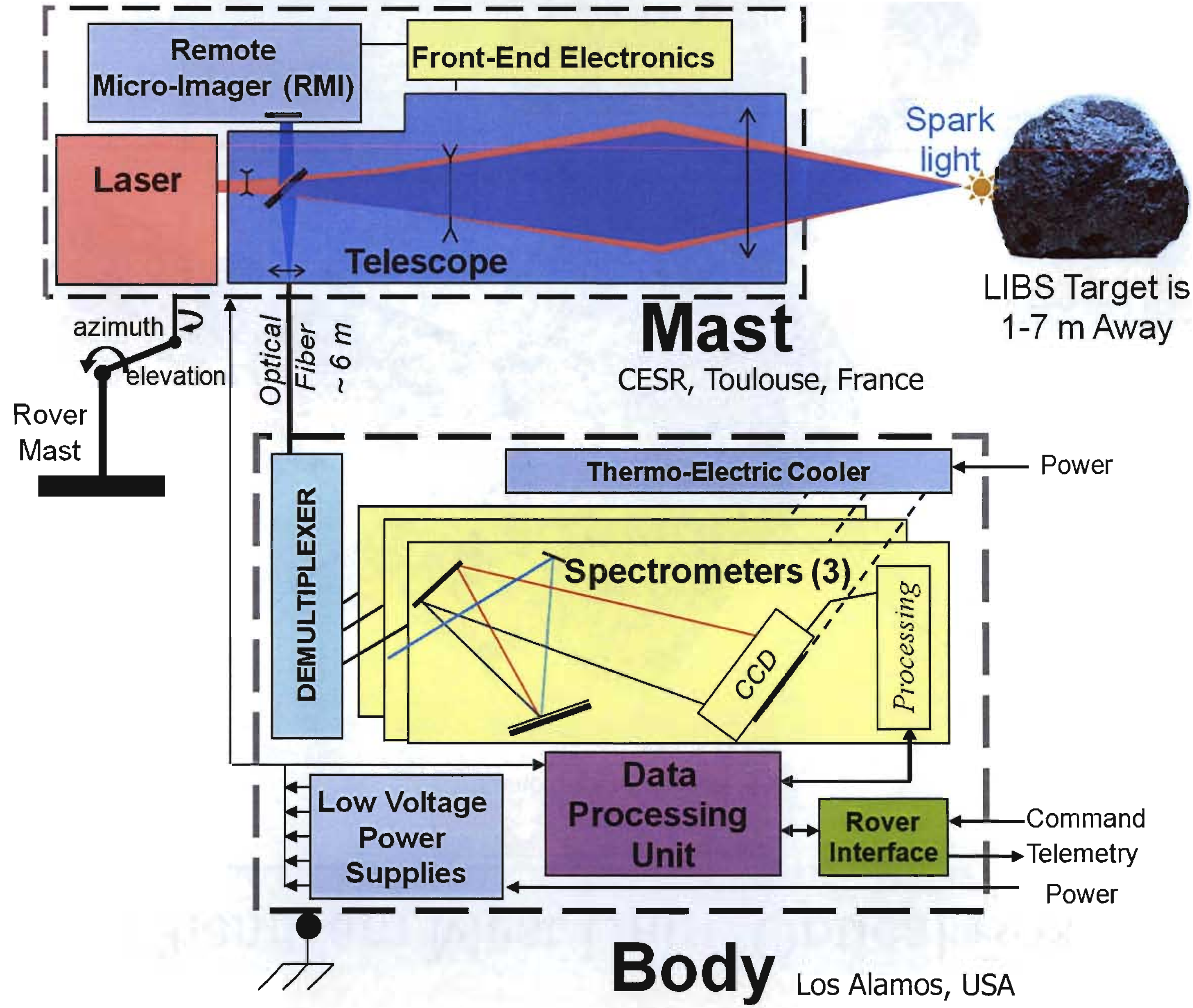
Top-Level Instrument Requirements

- Measure major elements to ±10% accuracy
- Analysis distances to 7 m
- Capable of up to 10 measurements/day
- Provide depth profiles to 1 mm deep
- Individual shot analyses
- Provide context images for analyses
- Provide rapid analyses (goal 5 min./analysis)

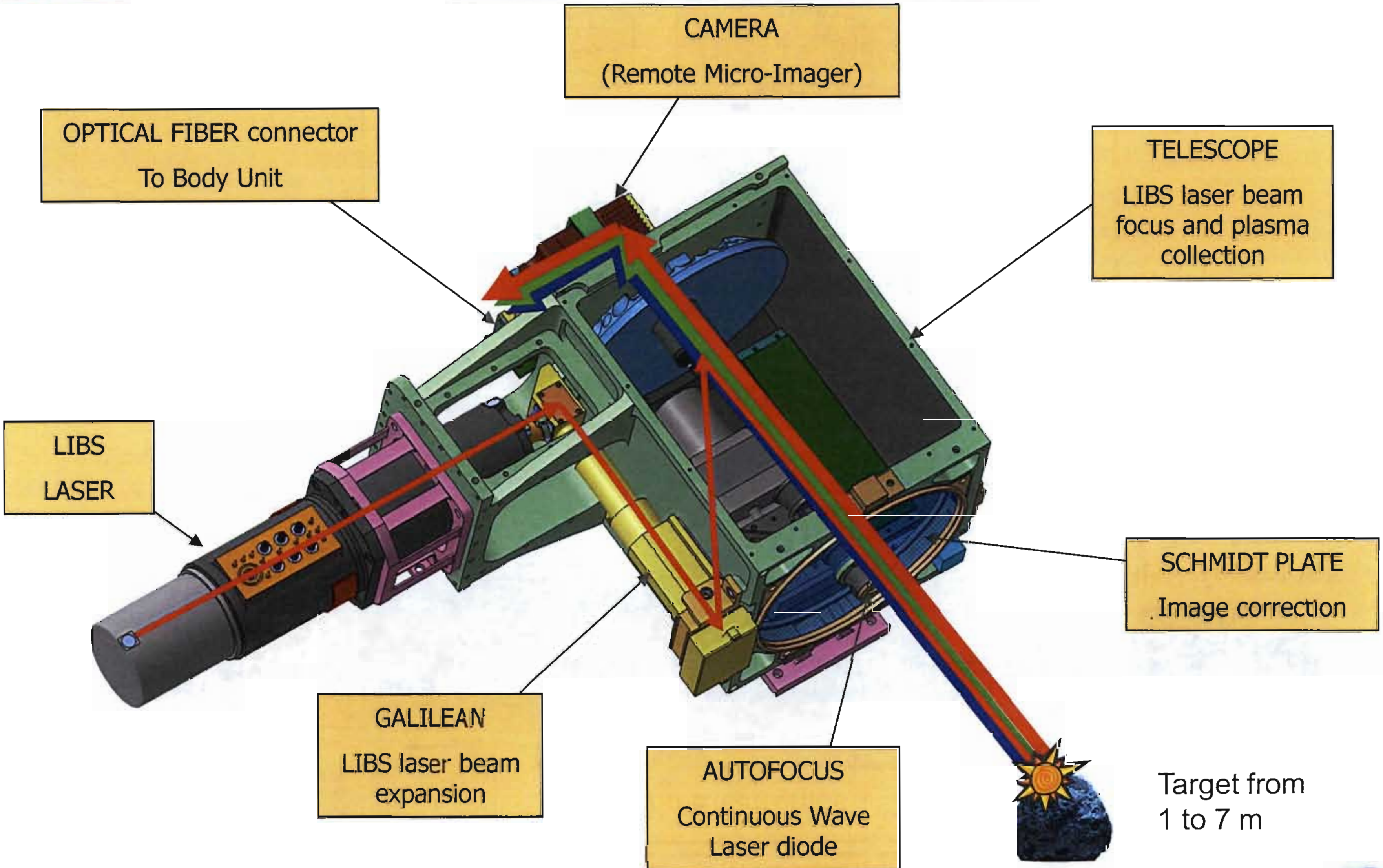
Derived Requirements

- Spectral range 242-800 nm
  - To cover C (strongest line 248 nm) and O (strongest line 777 nm)
- Spectral resolution
  - < 0.20 nm FWHM for < 470 nm
    - Separates 248 nm C line from Fe interference and 407.7 nm Sr line from Fe interference
  - < 0.65 nm FWHM for > 470 nm
    - Fewer and more widely spaced interferences in this spectral range
- Laser power density > 10 MW/mm^2
  - Needed to create LIBS sparks
- Imager resolution ≤ 100 μrad
  - To image LIBS analysis pits
- Laser rated to 5 million shots, passively cooled
- Requirements on transmission and signal-to-noise

ChemCam Instrument Schematic



ChemCam Mast Unit : Optical Box



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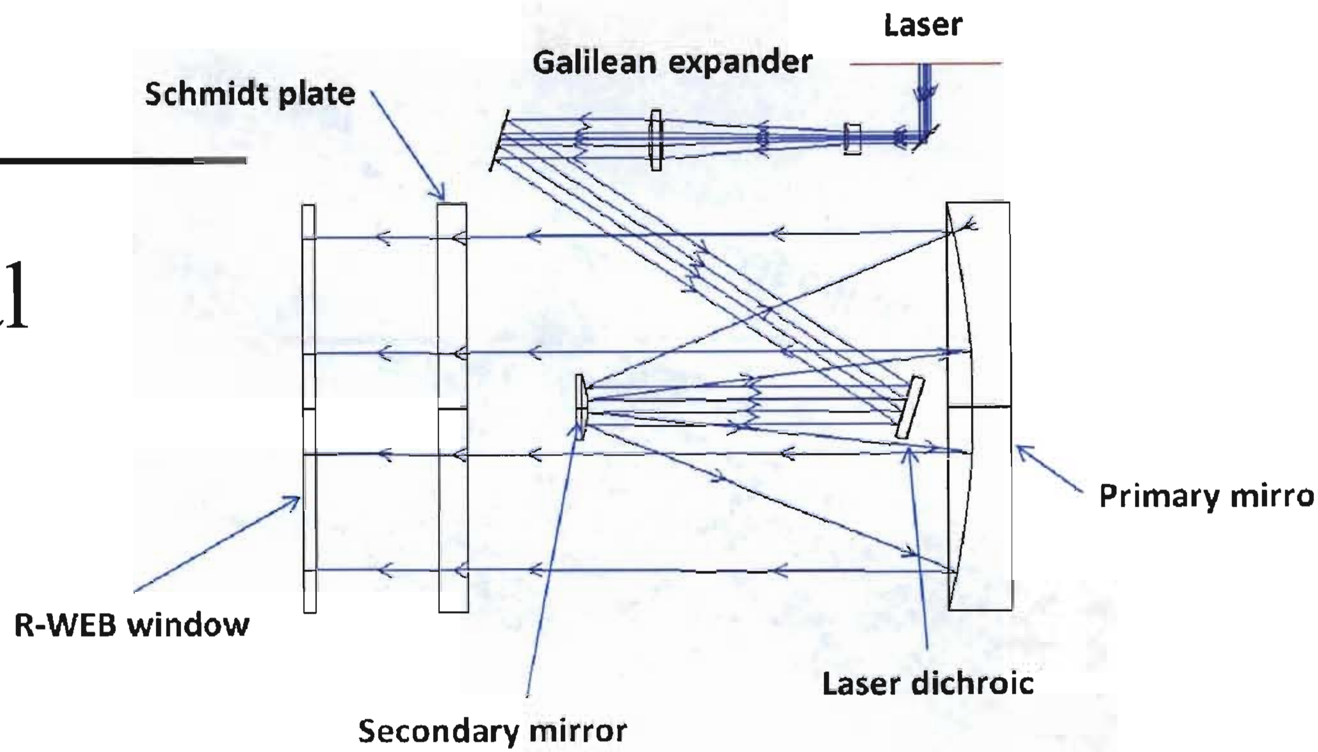
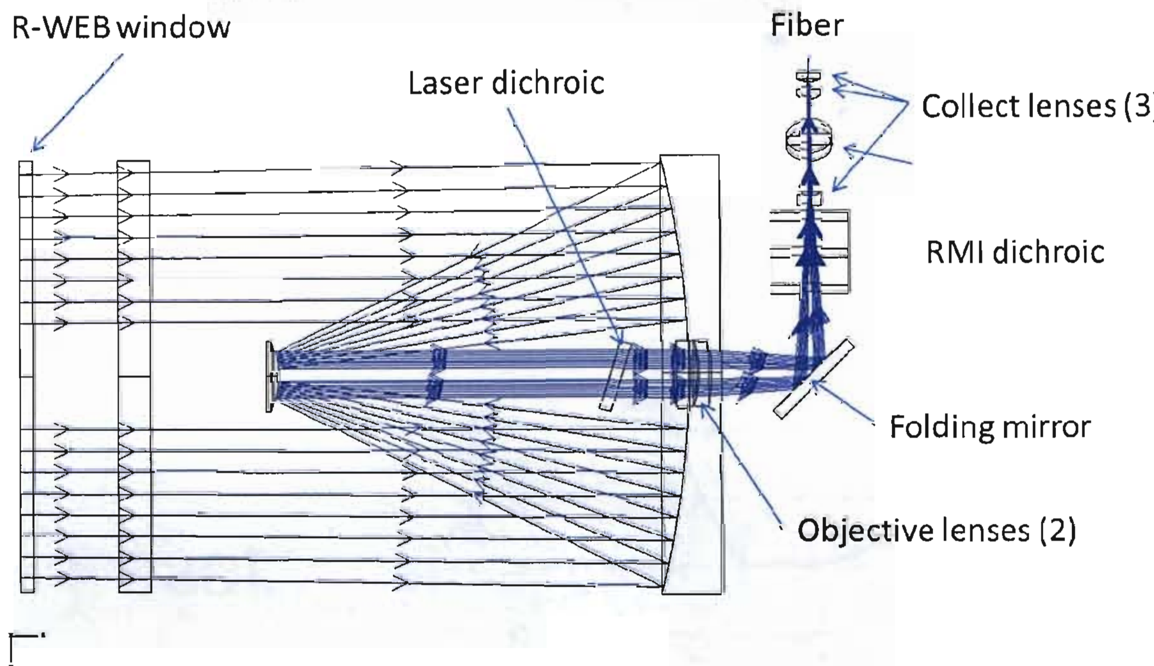
Optical Paths





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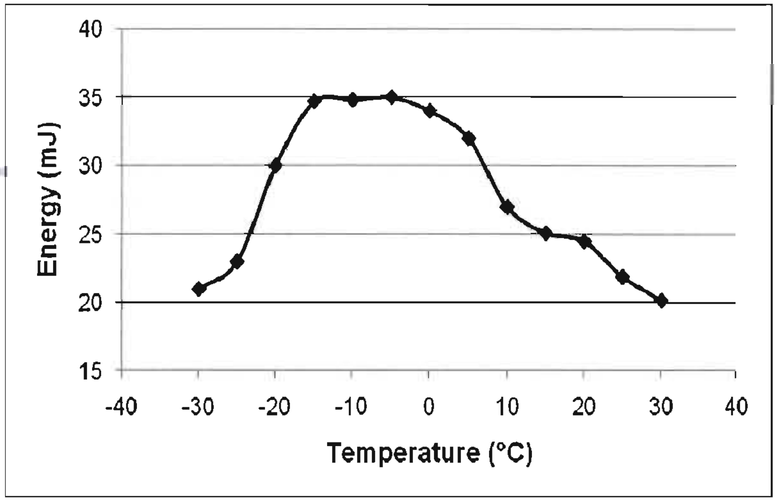
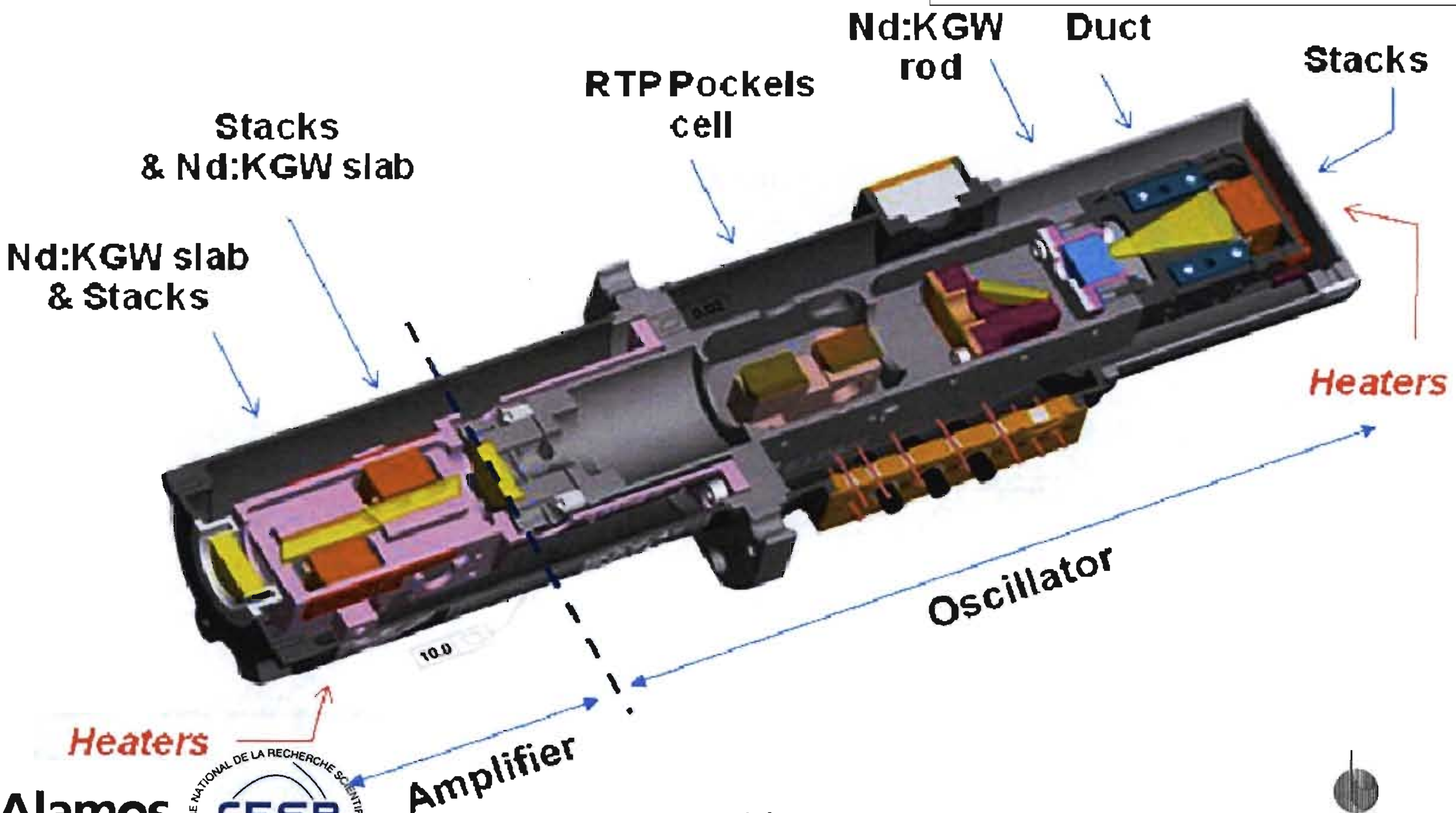
Laser

- Passively cooled
- Up to 35 mJ output
- ~500 g





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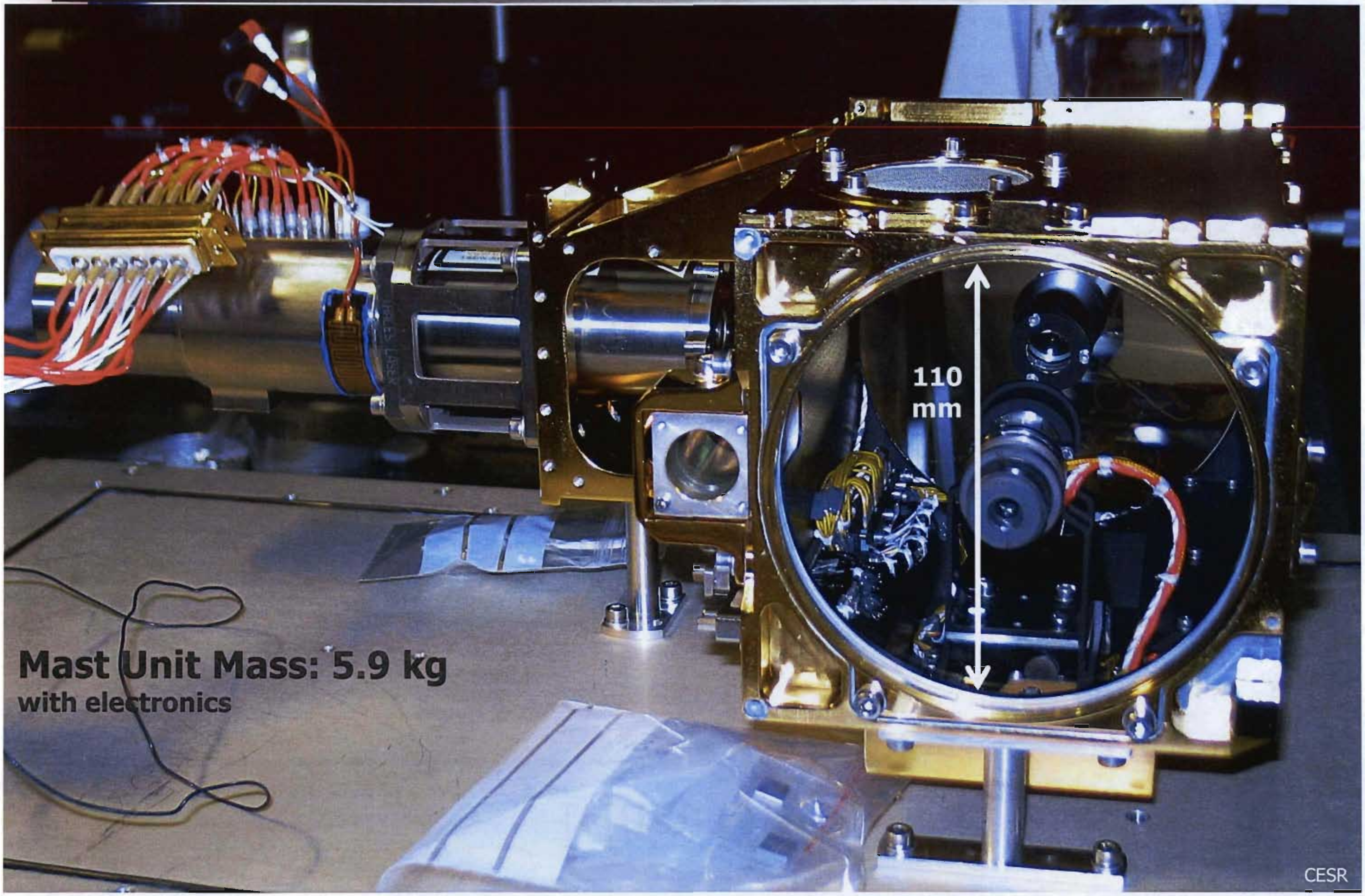
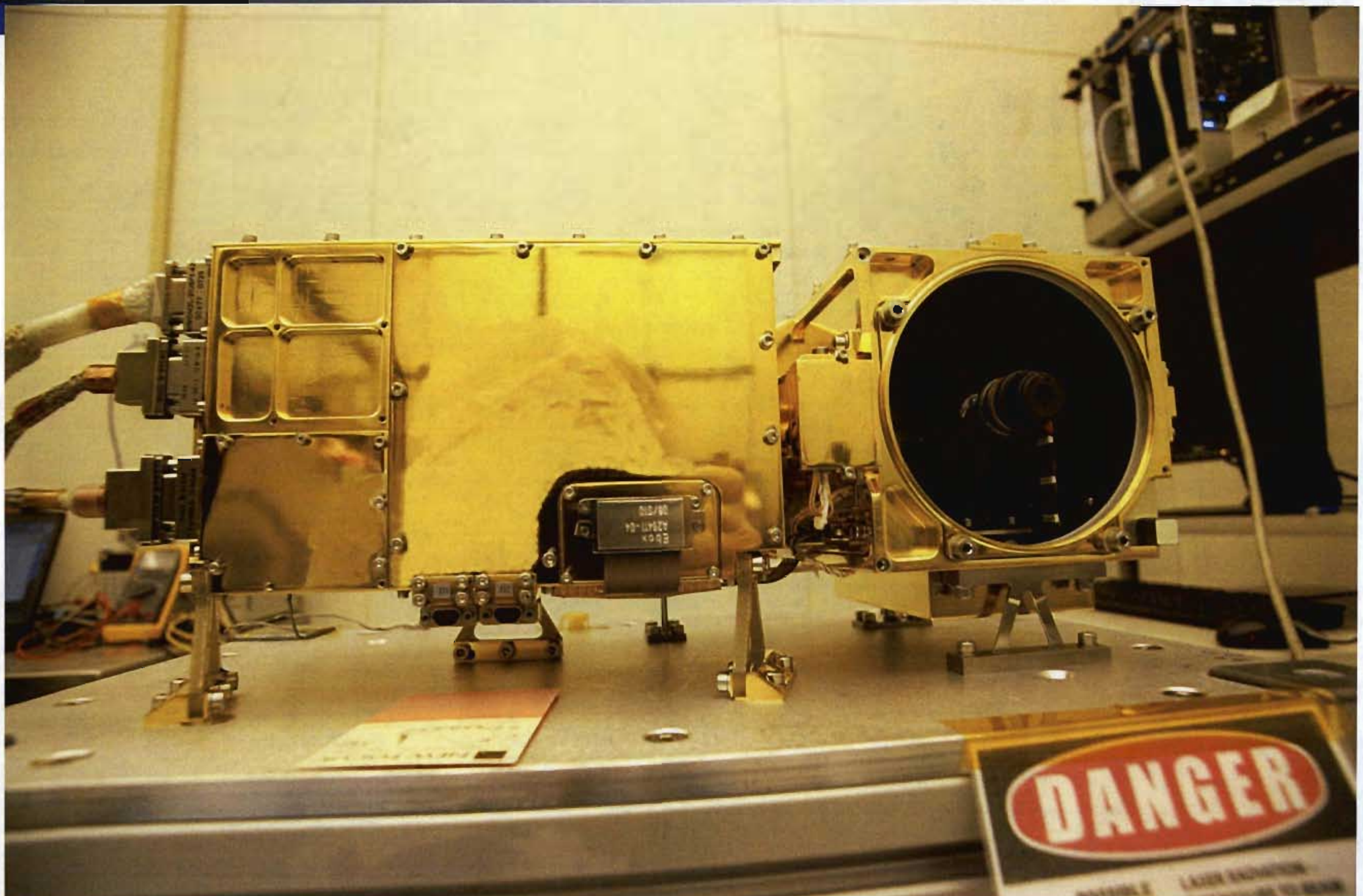
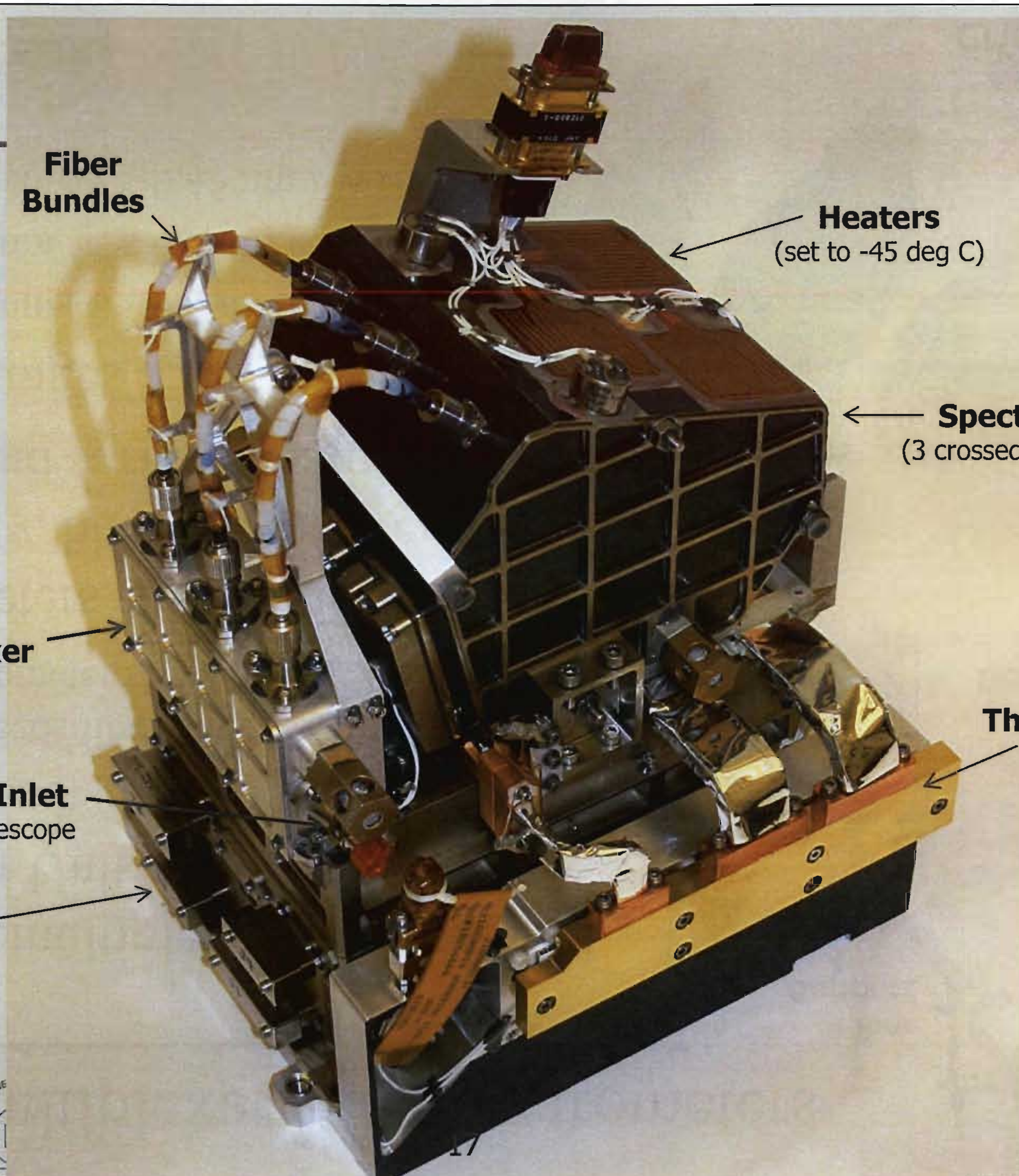
Laser & Telescope in Assembly



Mast Unit



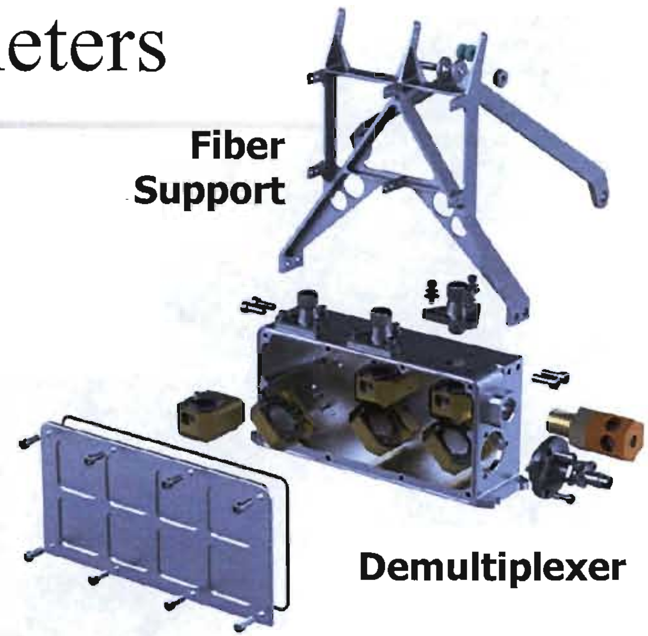
Body Unit



Fiber Bundles
Heaters
(set to -45 deg C)
Spectrometers
(3 crossed Czerny-Turner)
Optical Demultiplexer
Thermo-Electric Cooler
& cables
Fiber Inlet
From telescope
Electronics

Demultiplexer and Spectrometers

- Optical demultiplexer receives light from Mast Unit, optimizes light going to each spectrometer
  - Output feeds fiber bundles linearly aligned to spectrometer slits
- Spectrometers are identical structurally, but with different gratings and surface coatings
- Spectral ranges
  - 240-335 nm @ < 0.2 nm FWHM
  - 385-465 nm @ < 0.2 nm FWHM
  - 500-850 nm @ < 0.45 nm FWHM



Mast Unit Installation

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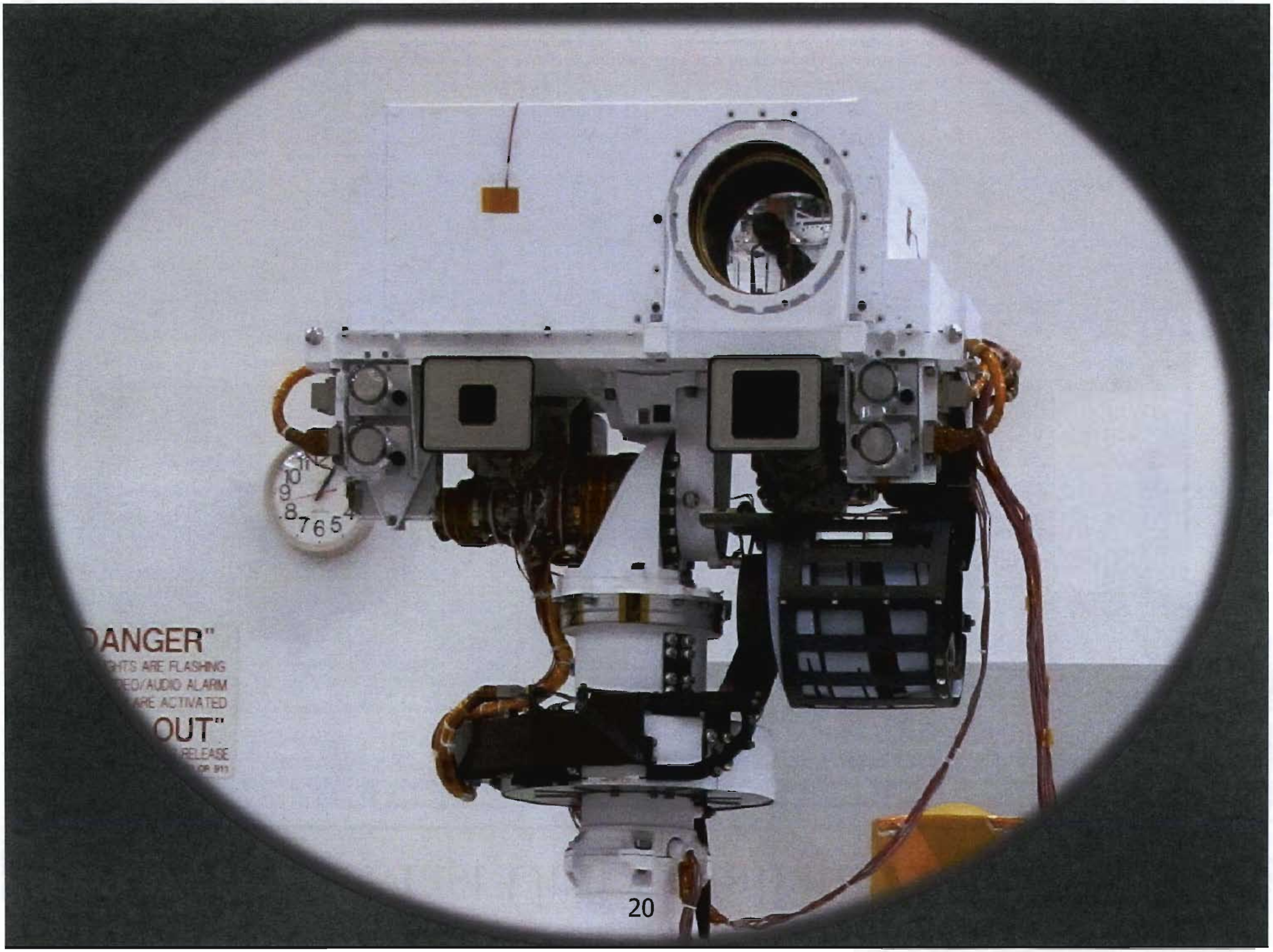
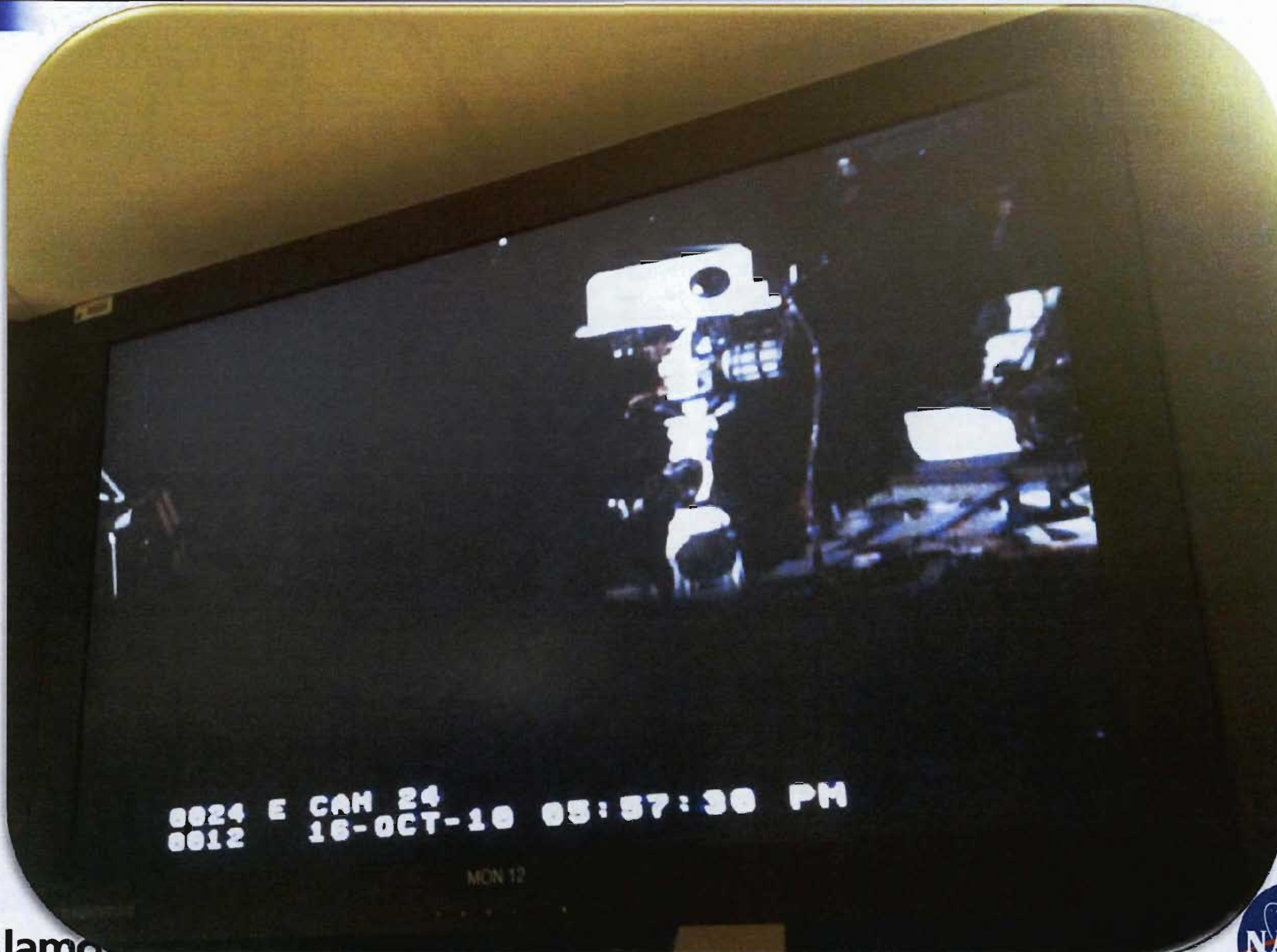
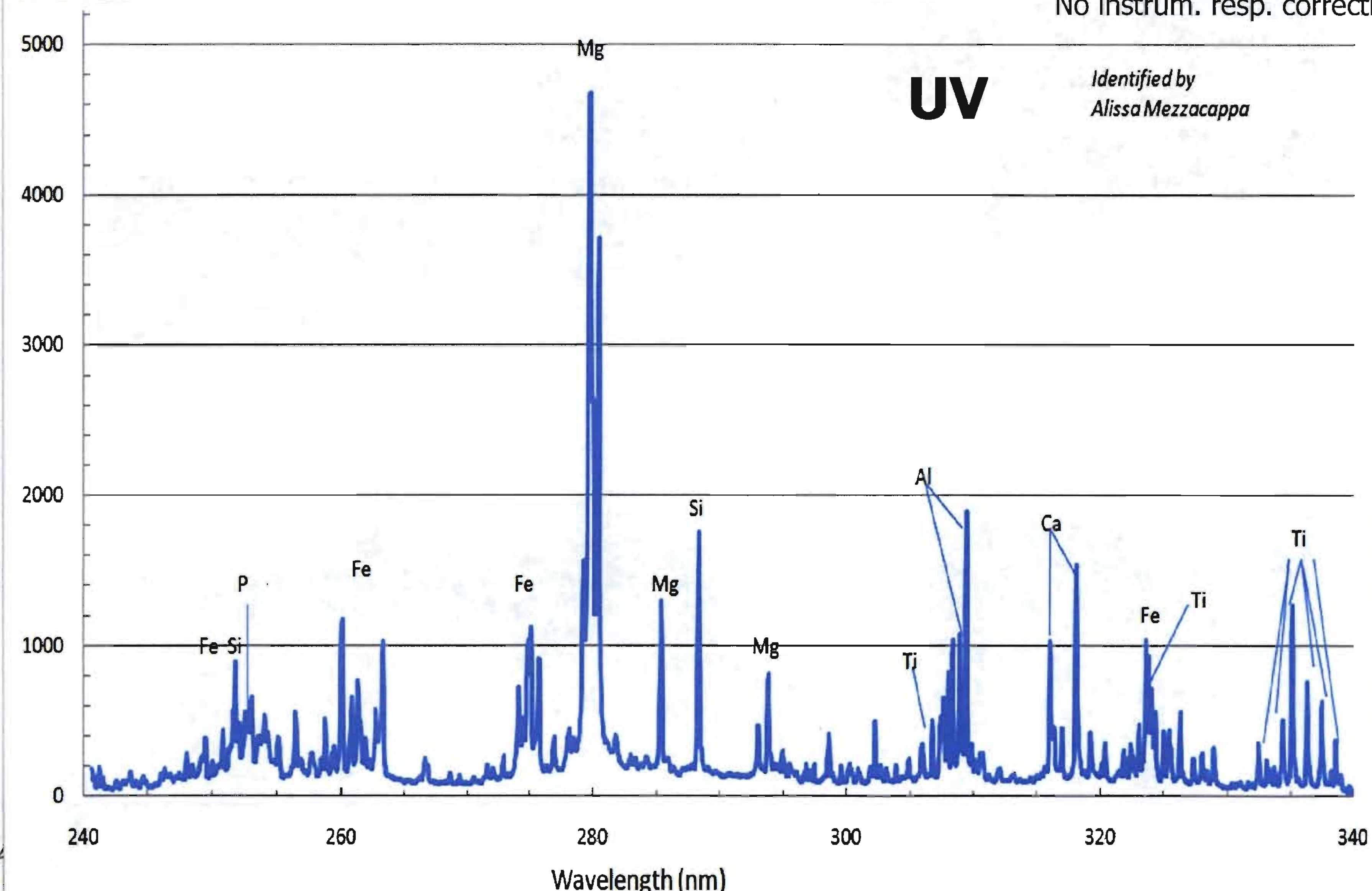


Rover During ChemCam Testing



LIBS Spectrum

BT-2 basalt pressed pwdr
3 m, 95 A during T-V
In 7 Torr CO2
No instrum. resp. correction



Taken at LANL

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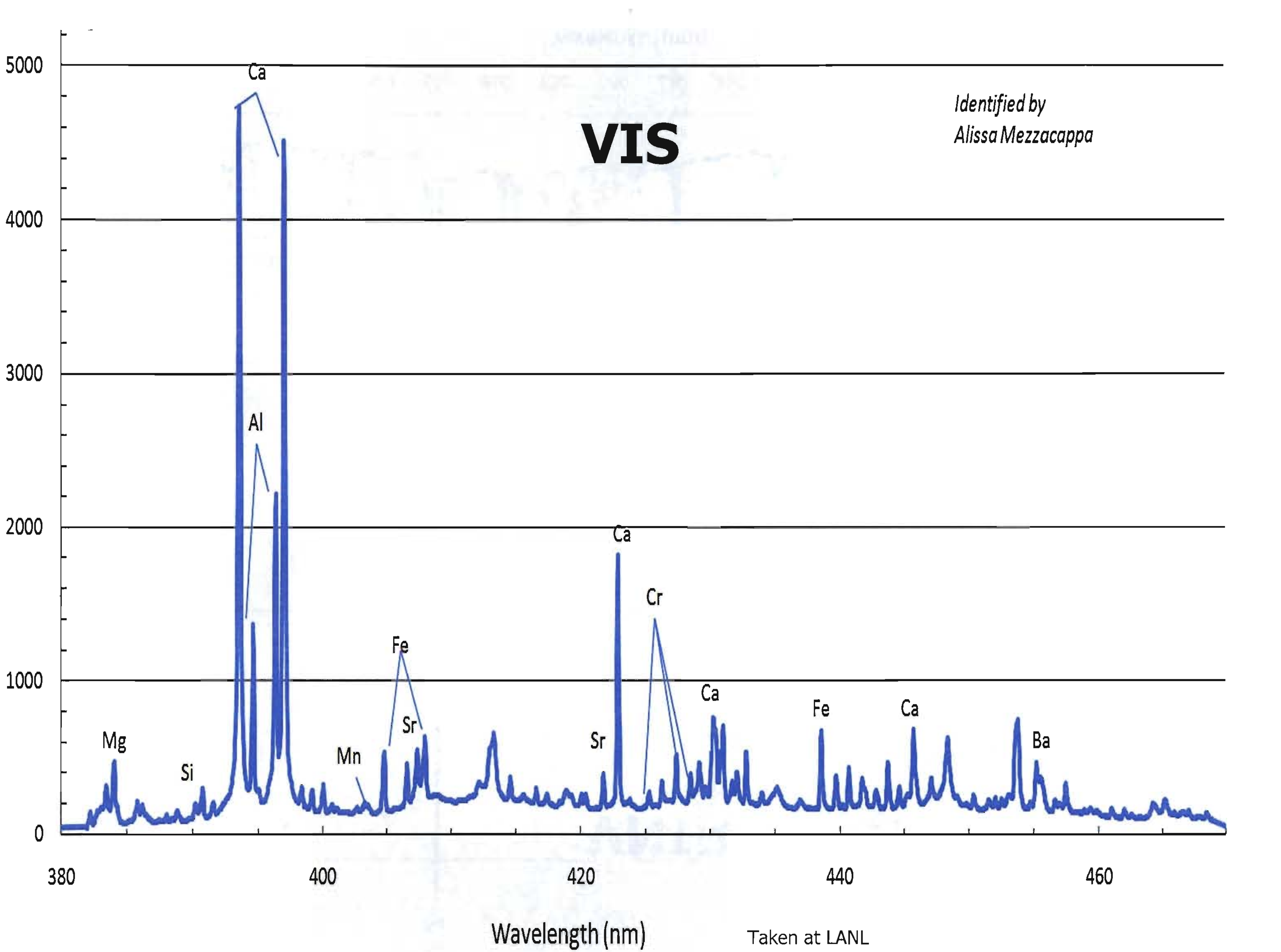
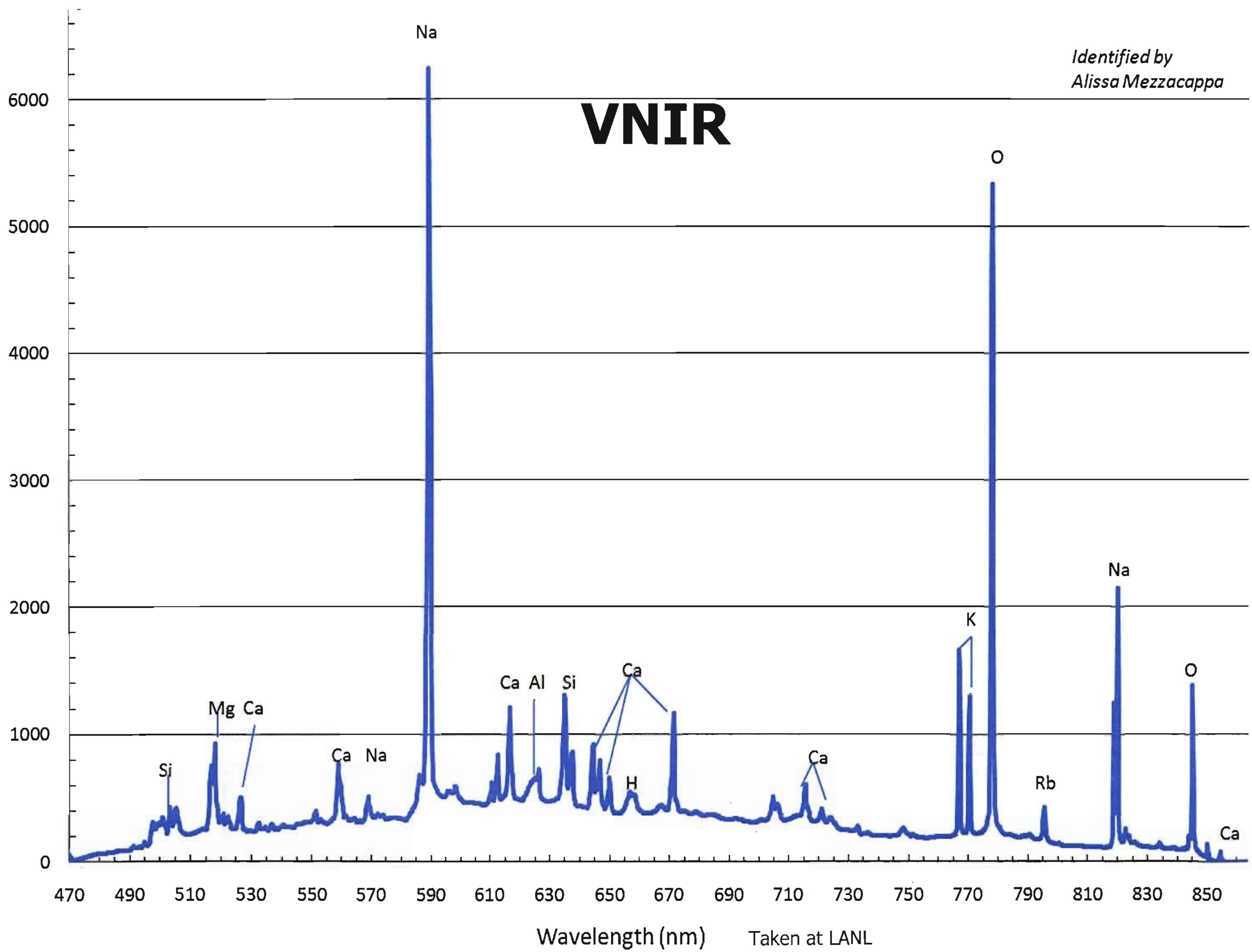
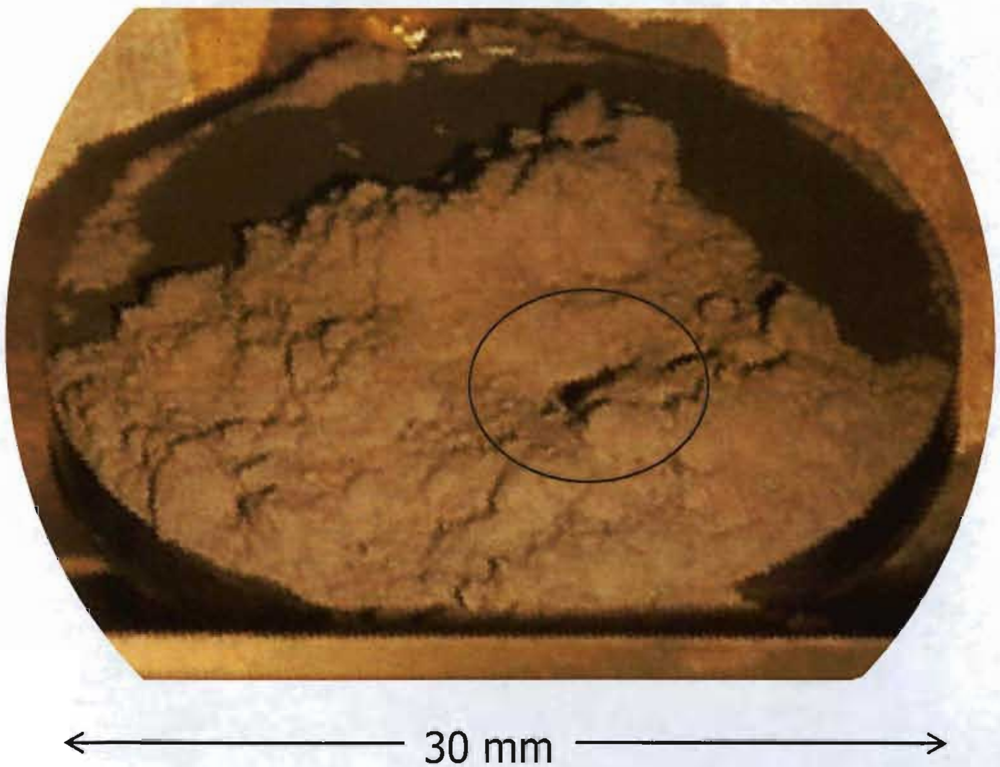
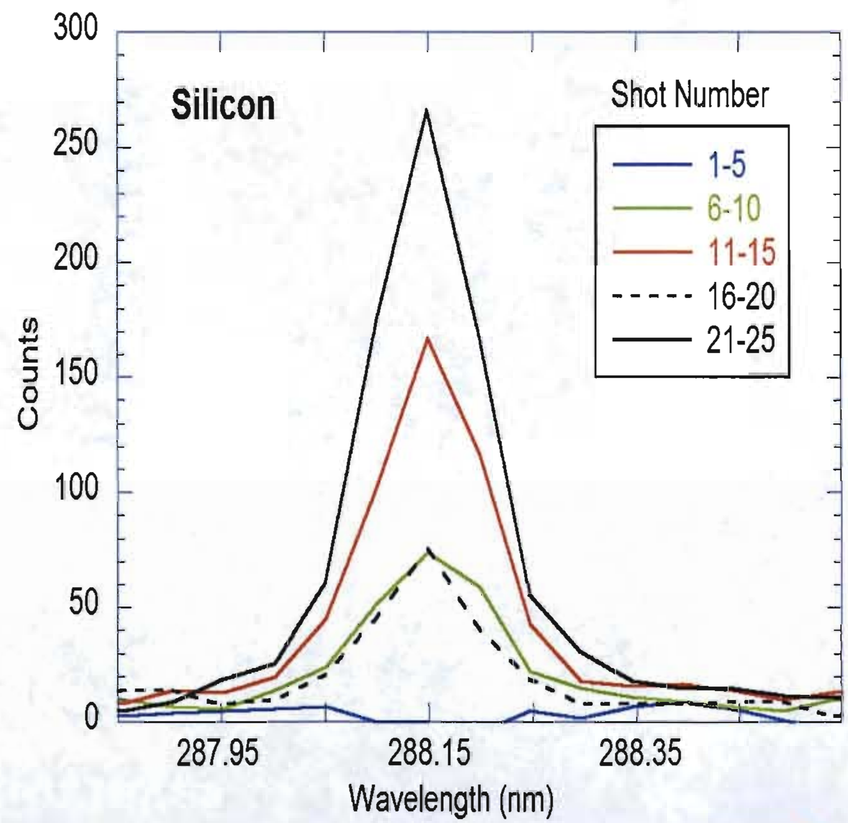

VIS
Identified by
Alissa Mezzacappa
5000
4000
3000
2000
1000
0
380
400
420
440
460
Wavelength (nm)
Taken at LANL
Ca
Al
Mg
Si
Mn
Fe
Sr
Ca
Sr
Cr
Ca
Fe
Ca
Ba


VNIR
Identified by
Alissa Mezzacappa
Na
O
K
Na
O
Ca
Rb
Ca
Ca Al Si
Ca
H
Mg Ca
Si
Ca Na
6000
5000
4000
3000
2000
1000
0
470 490 510 530 550 570 590 610 630 650 670 690 710 730 750 770 790 810 830 850
Wavelength (nm)
Taken at LANL

Dust Removal

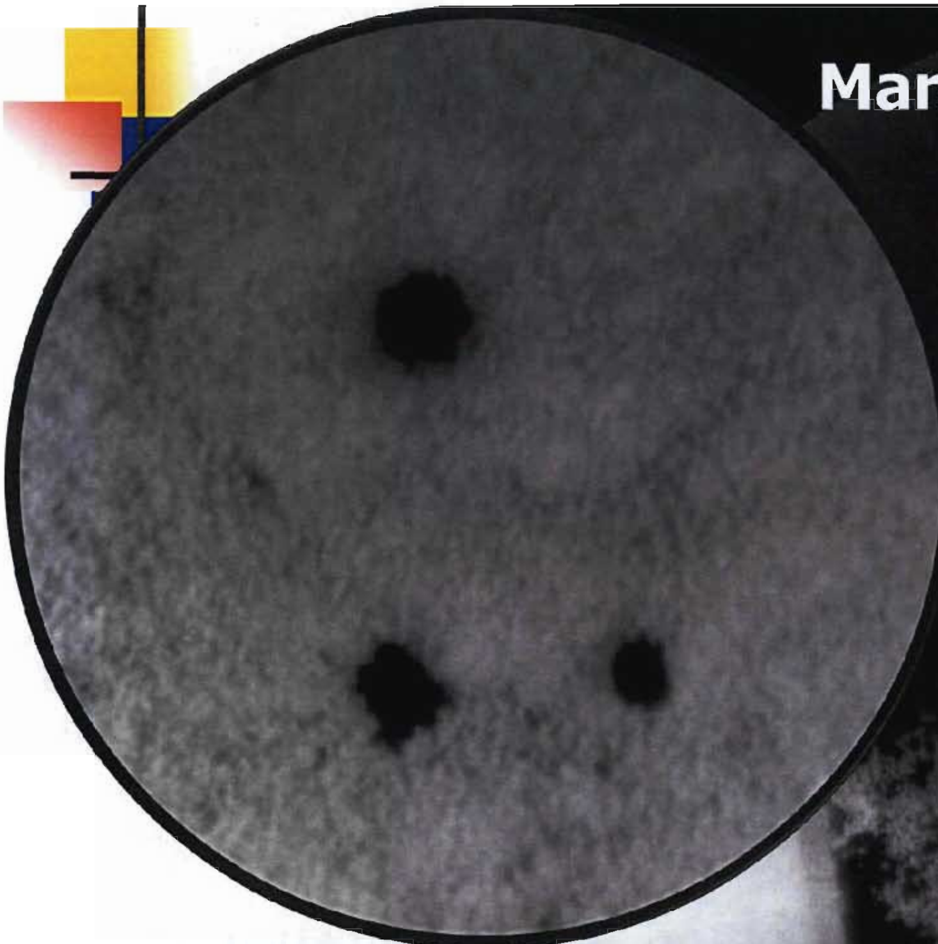
- Tested at 3.5 m in Mars atmosphere
  - Several mm of dolomite dust on basalt disk
  - Watch silicon peak grow in

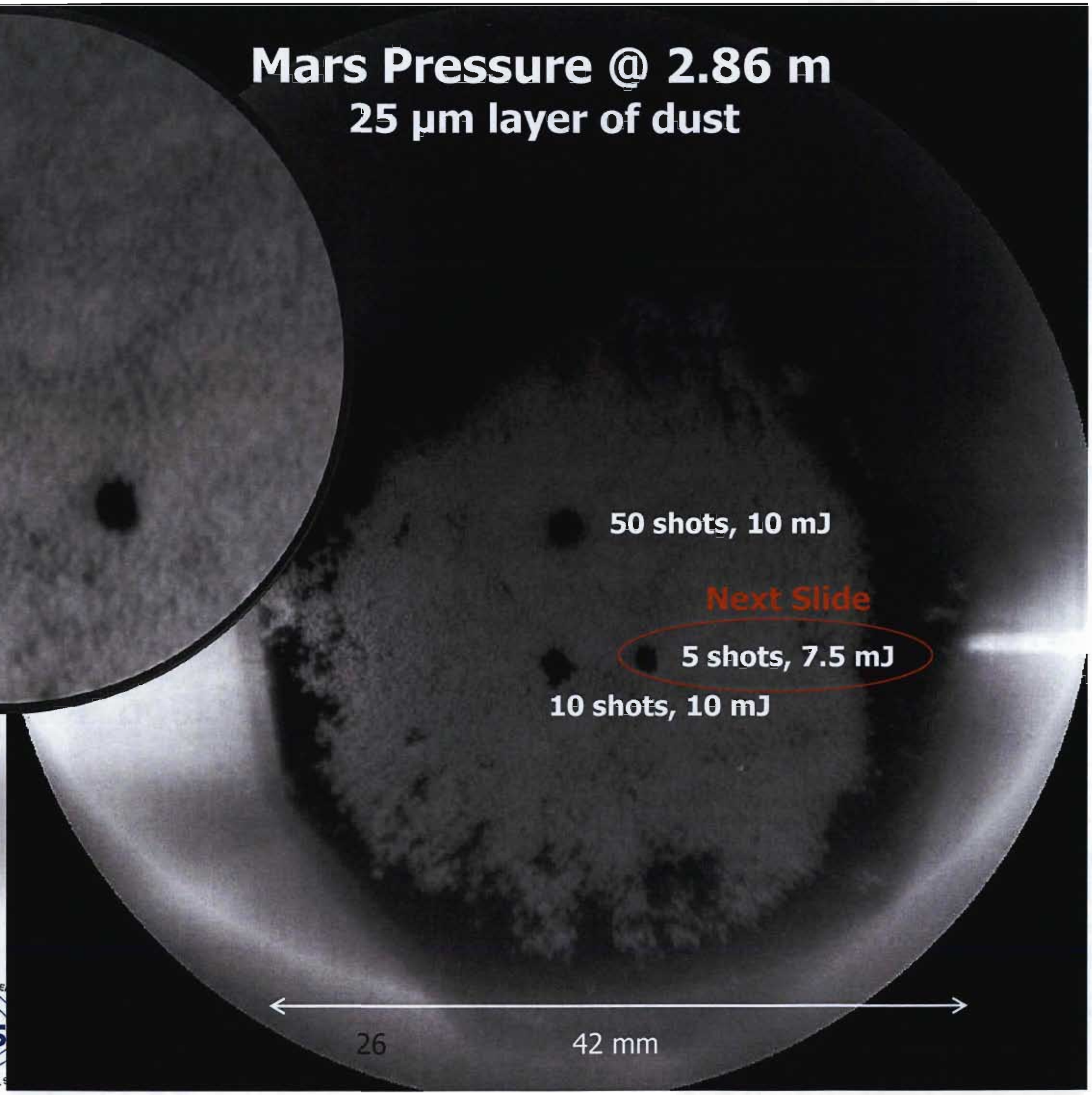




Mars Pressure @ 2.86 m

25 μm layer of dust





Diameters between 1.5 and 2.4 mm

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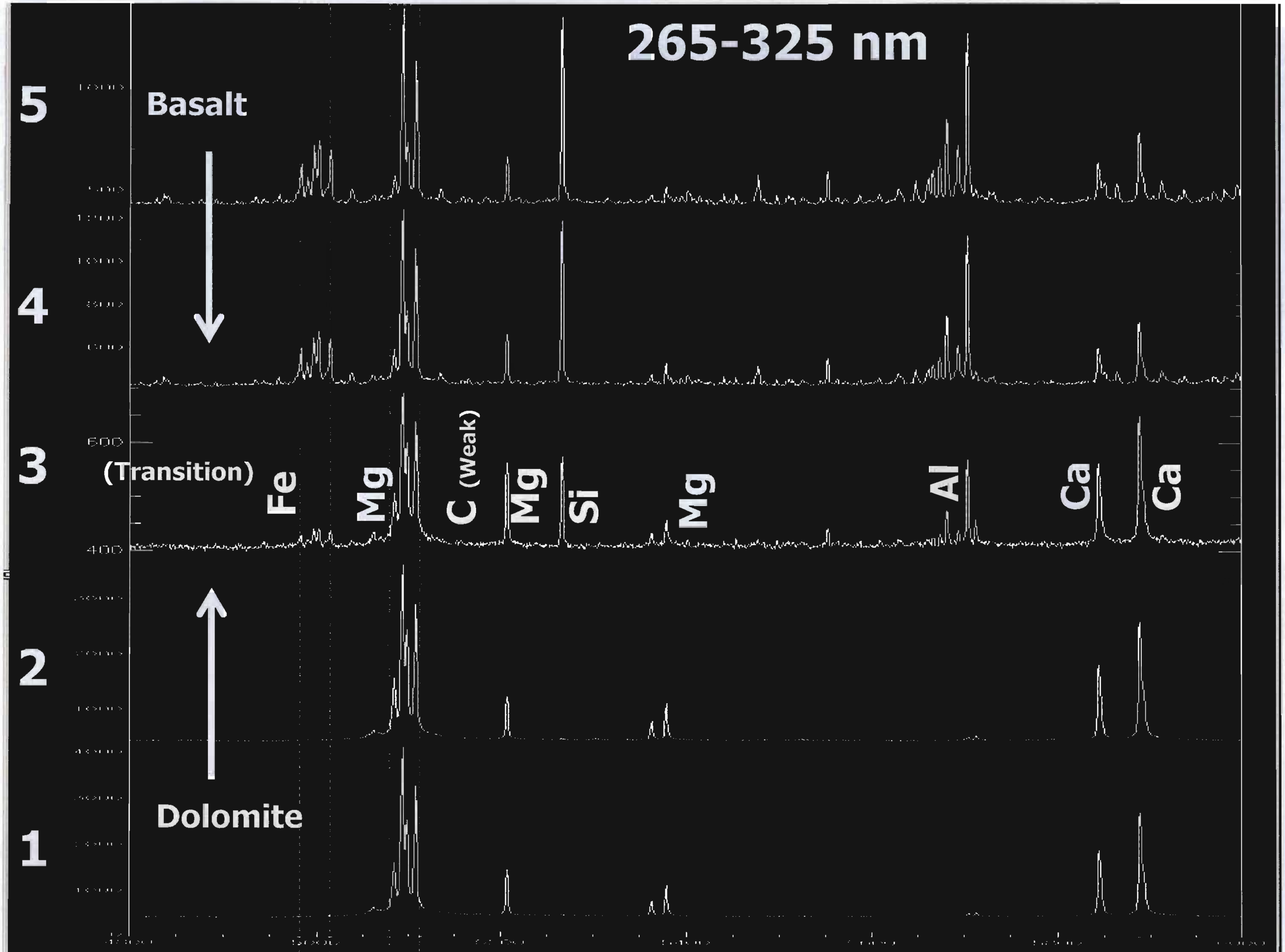
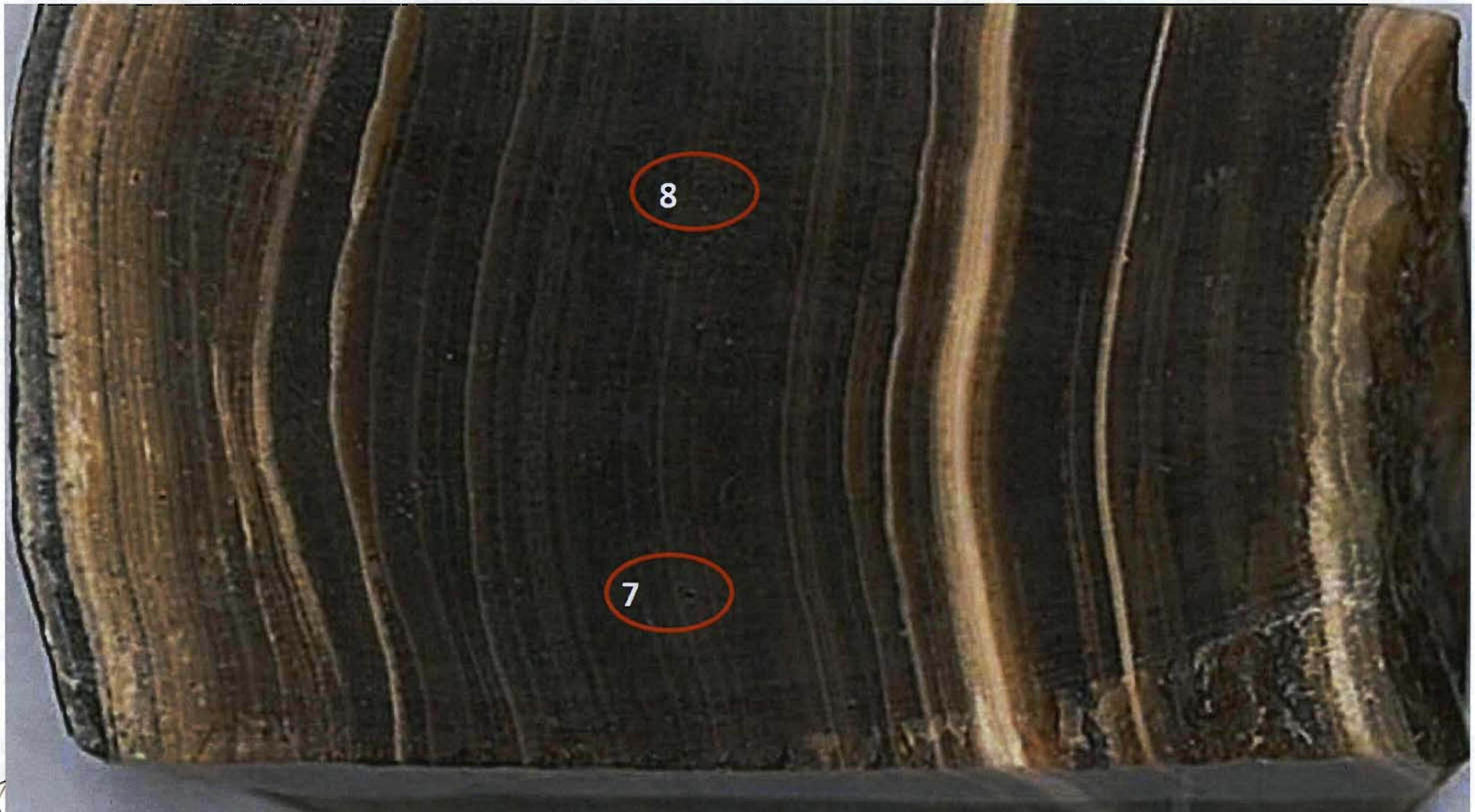
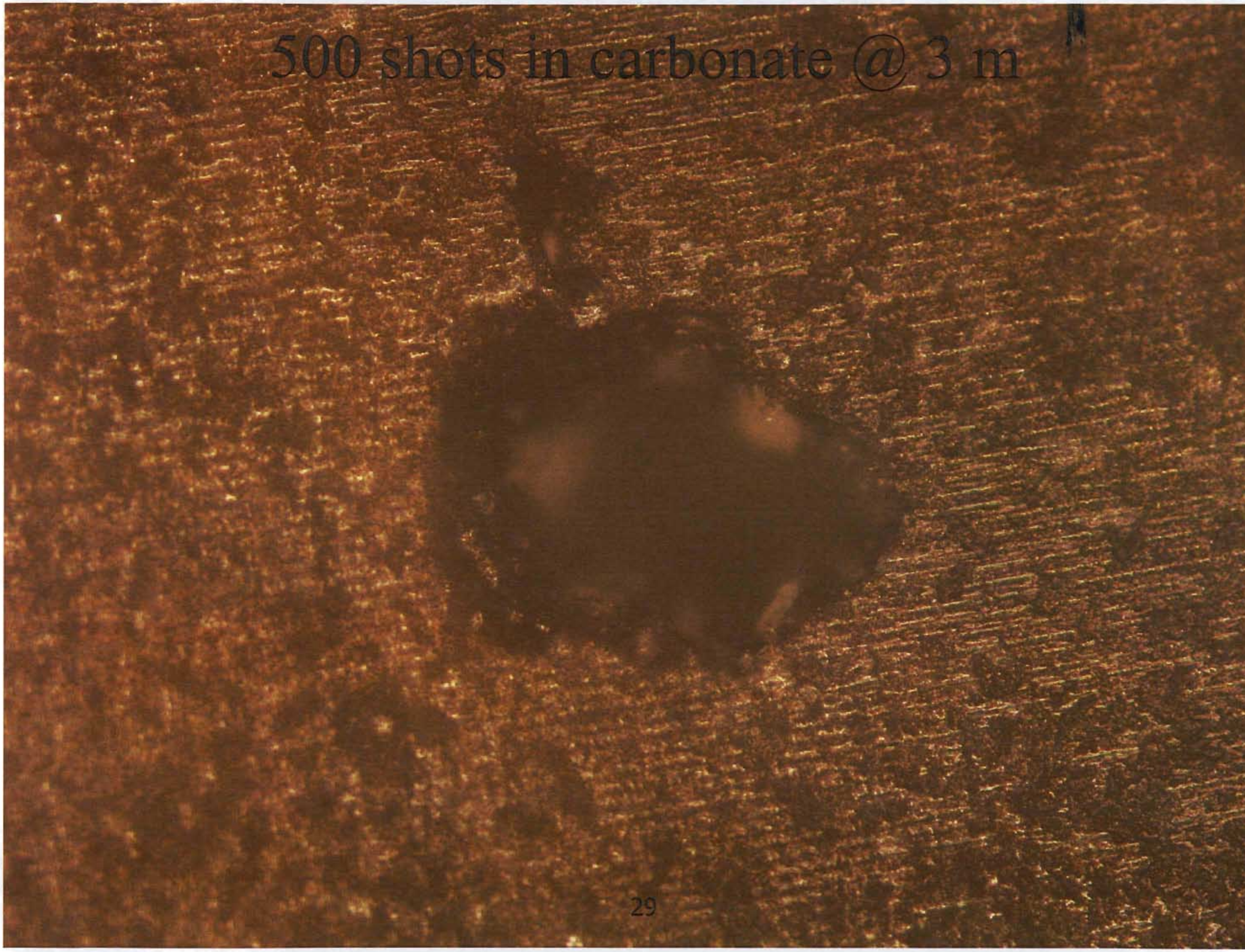


265-325 nm
5
Basalt
4
3
(Transition)
Fe
Mg
C (Weak)
Mg
Si
Mg
Al
Ca
Ca
600
400
2
1
Dolomite

Depth Profile in Carbonate @ 3 m

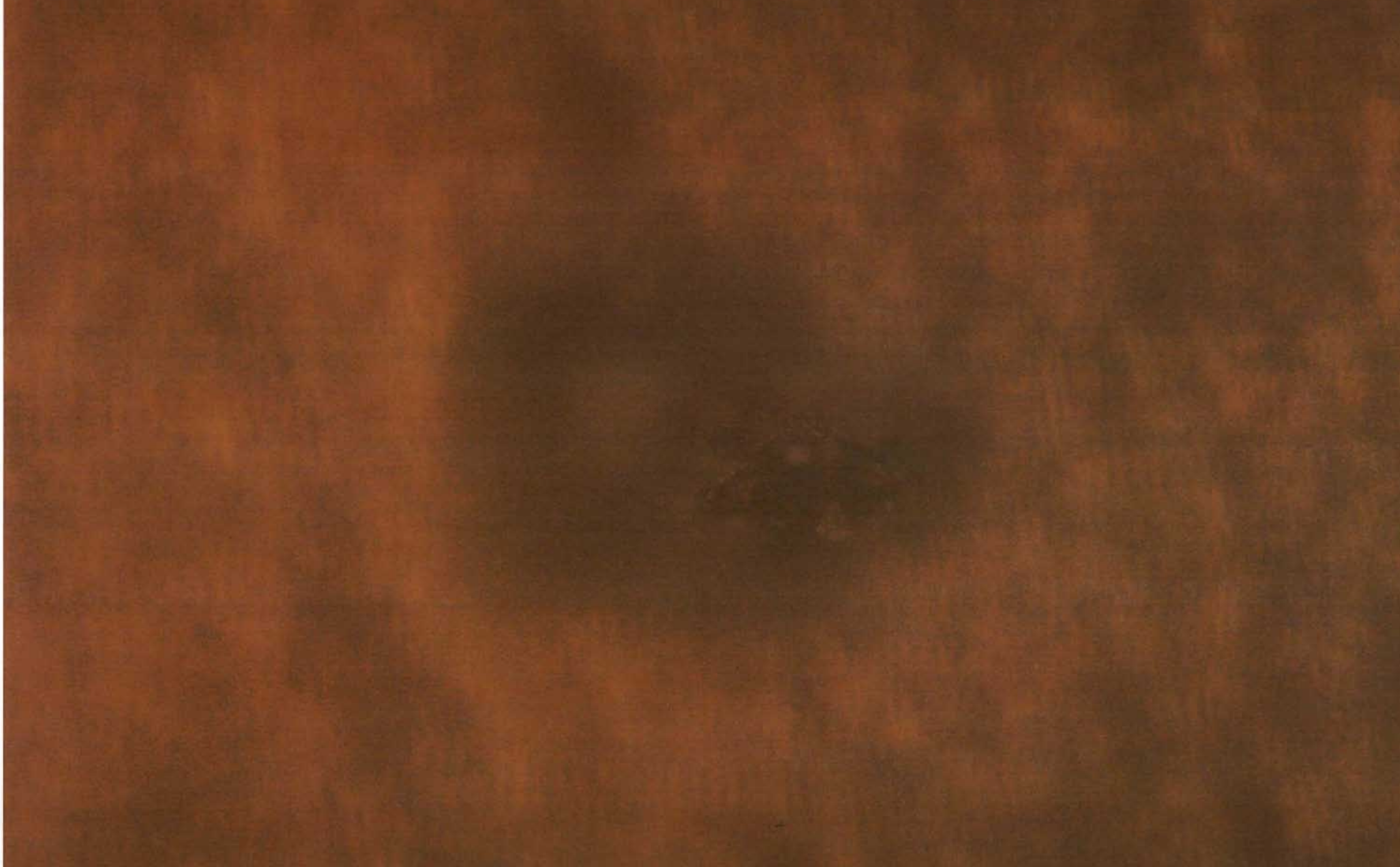


500 shots in carbonate @ 3 m



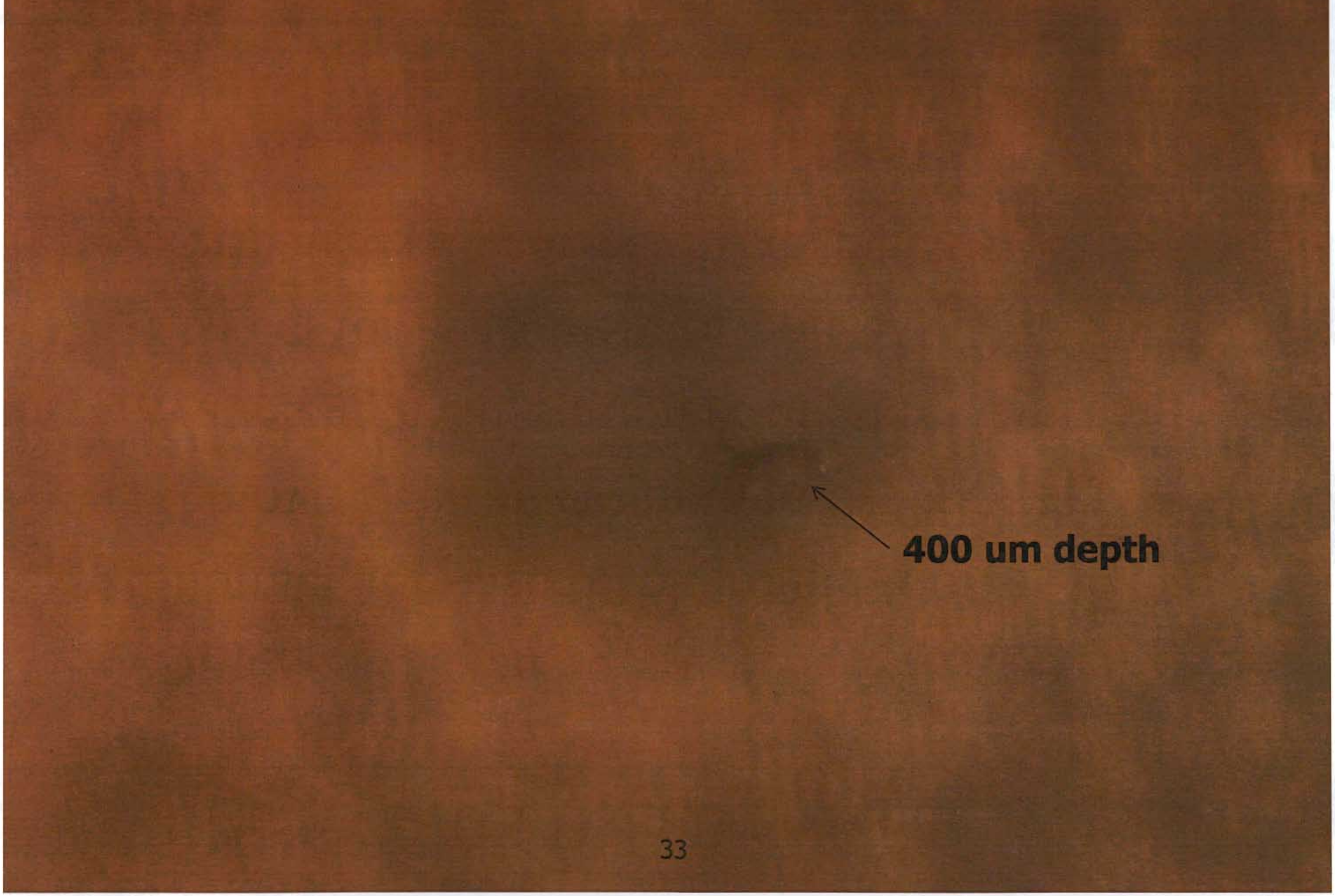
500 shots in carbonate @ 3 m

500 shots in carbonate @ 3 m



500 shots in carbonate @ 3 m

500 shots in carbonate @ 3 m



LIBS Data Processing

- Sanity check and de-noise
- Subtract non-laser background file
- Remove electron continuum
- Wavelength calibration & pixel re-sampling
- Correct for instrument response
- Normalize and correct for distance

LIBS Data Analysis—Test for Quality

- Use pressed rock powders for homogeneous samples
- Averaged ~50 spectra on the same spot
- Analyzed 4 different spots per sample
- 11 different samples analyzed
- Classification methods:
  - Euclidean Distance
  - Sammon's Map
  - Independent Component Analysis
- Quantification: Partial Least Squares Regression (PLSR)

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Projection and clustering methods

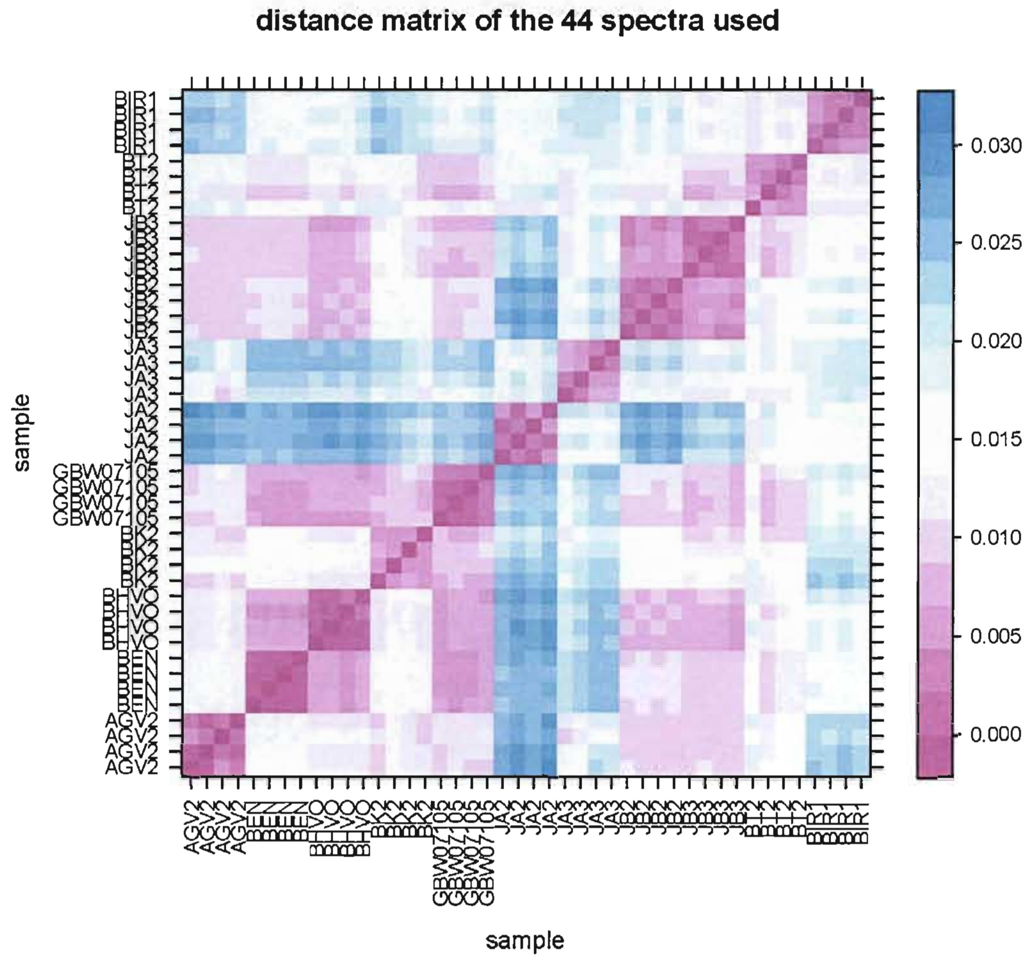
Igneous rocks at 5 m thermo-vacuum tests

Euclidean distance matrix of the 44 spectra used

Euclidean distance gives a good clustering of the different samples

4 clusters can be seen: BIR1; JA2; JA3; other samples

Useful to detect outliers in the dataset



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3. Projection and clustering methods

Igneous rocks at 5 m thermo-vacuum tests

Non-linear Bi-dimensional projection minimizing:

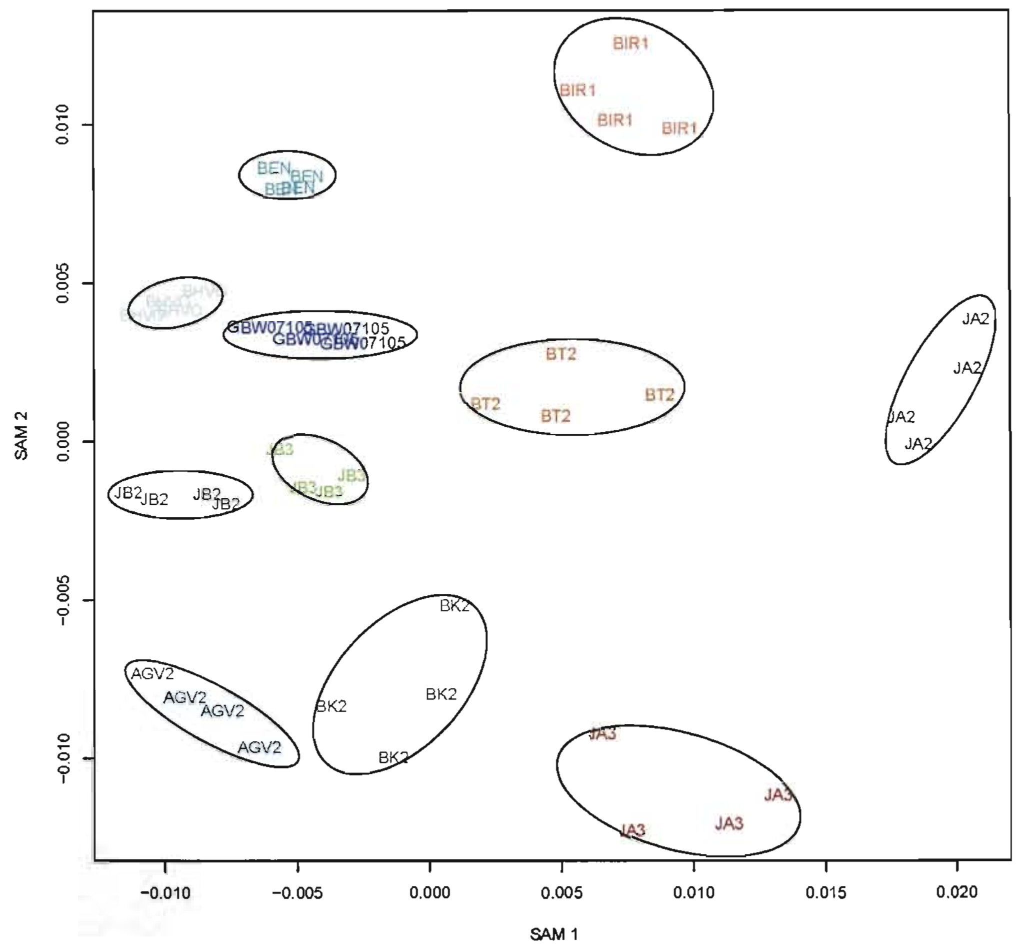
$$E = \frac{1}{\sum_{i<j} d^*_{ij}} \sum \sum_{i<j} \frac{(d^*_{ij} - d_{ij})^2}{d^*_{ij}}.$$

d_{ij}=initial space distance between i and j
d^*_{ij}=map distance between i and j

•In this case 2 times better than PCA for visual representation of the dataset.

ICA planned to be used by ChemCam

Sammon's map



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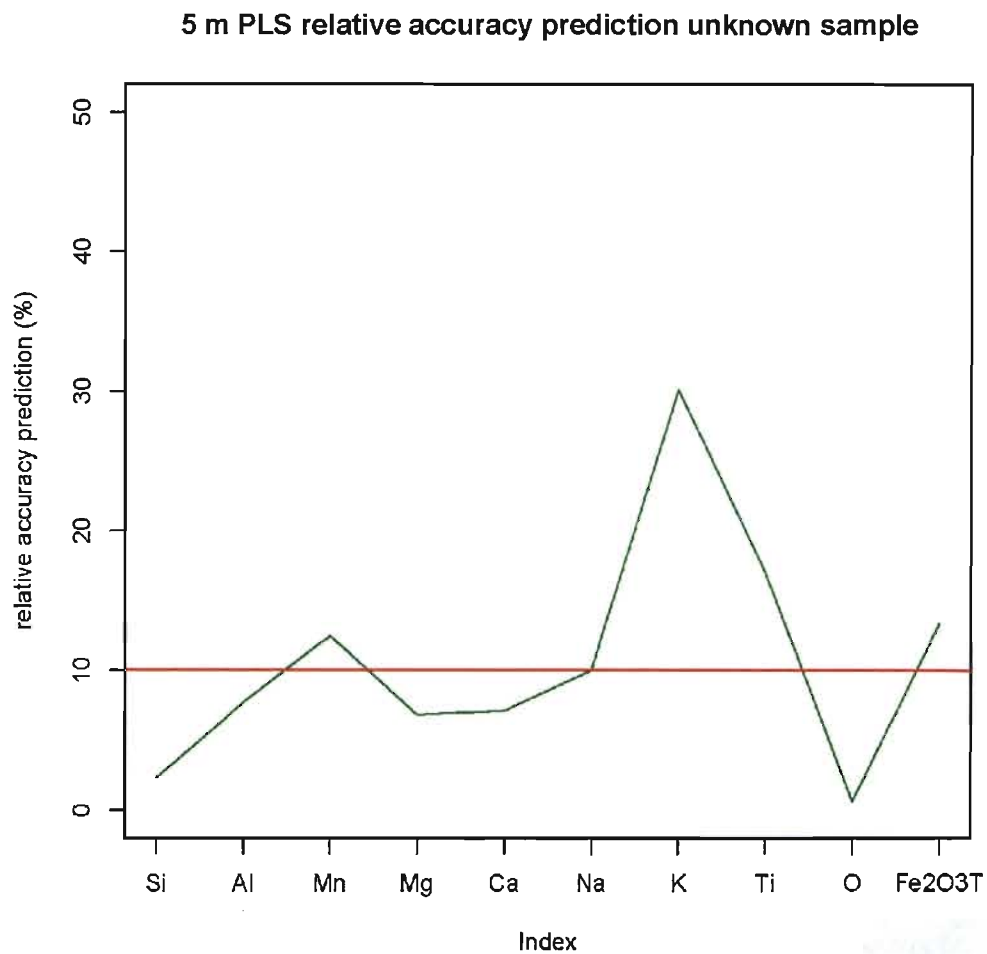
Quantification of elemental composition

Results PLSR at 5 m thermo-vacuum tests for 11 igneous standards

- Using PLSR, the median of the relative accuracy predictions for unknown samples is shown (one sample left out statistics).
- The accuracy of the predictions are typically of the order of 10% or lower.

- The quantities of Mn, K, Ti to be predicted are the lowest ($<10^{-3}$) which can explain the relative accuracy increase.



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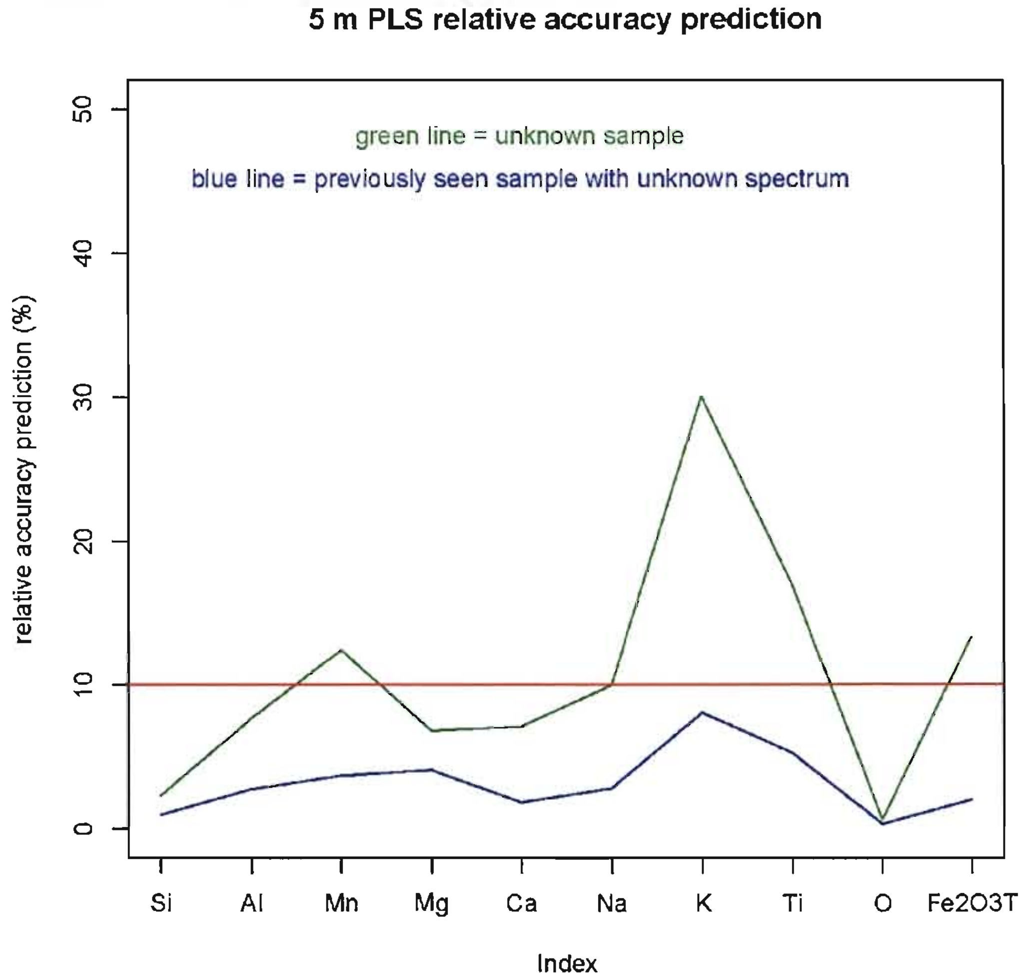
Quantification of elemental composition

Results PLSR at 5 m thermo-vacuum tests

- Here, the PLS model includes some spectra of the sample we are trying to predict.
- The accuracy of the predictions are 10% or lower for all elements.
- The predicted spectrum is never used to generate the model.
- Calibration based on most similar analogues will give best results.



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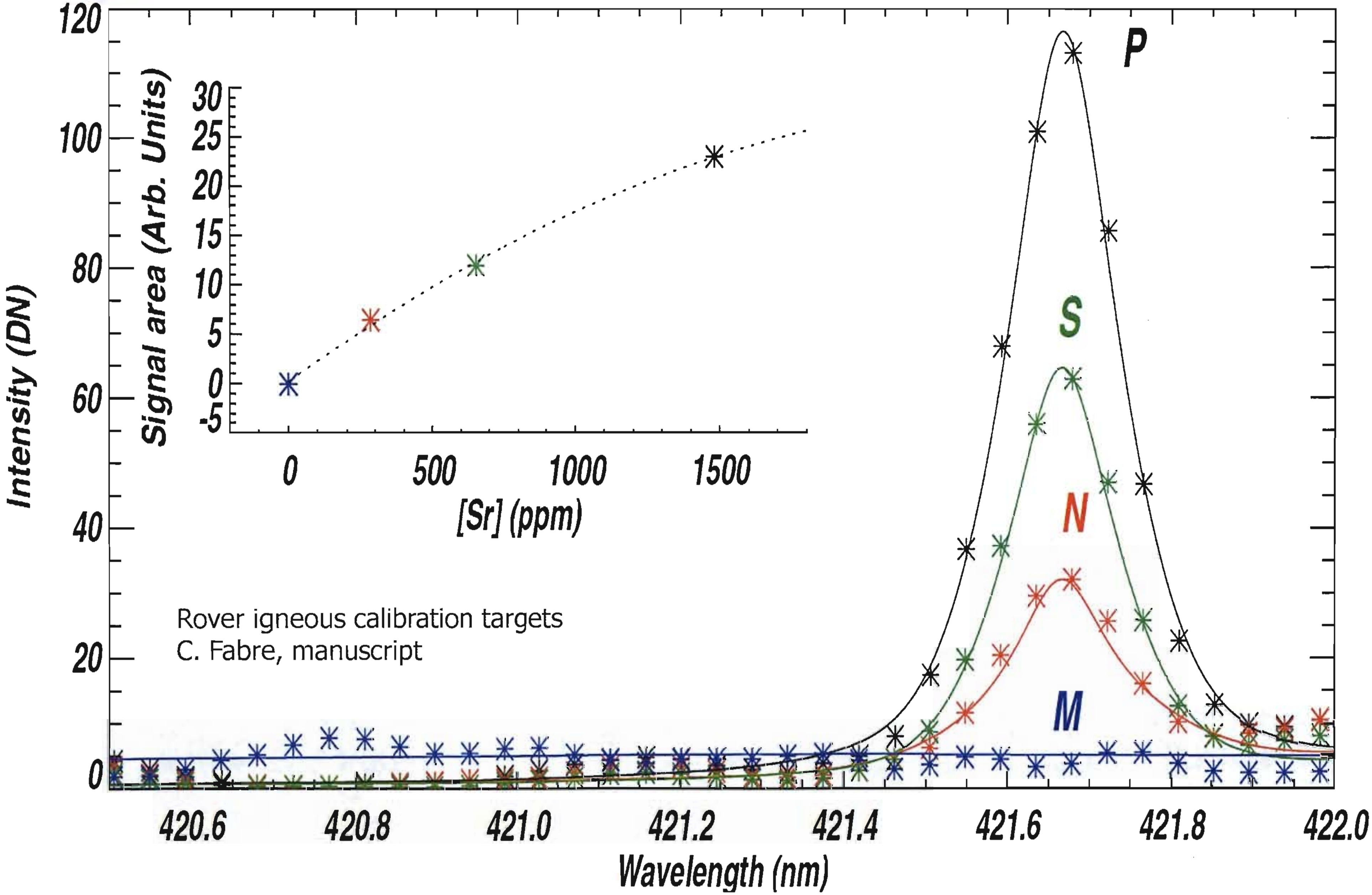
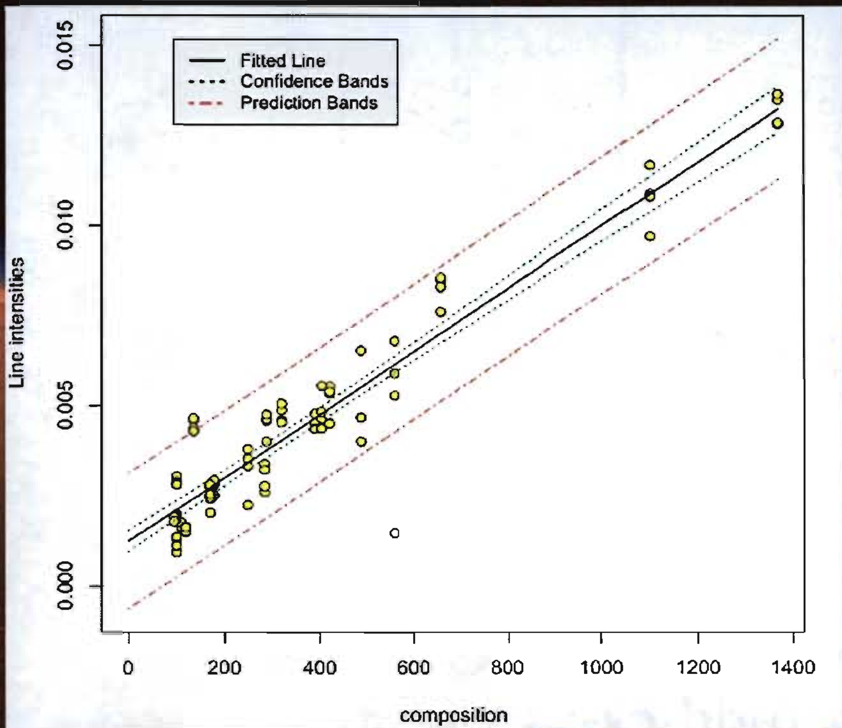
LIBS Minor & Trace Elements--Sr



LIMITS OF DETECTION

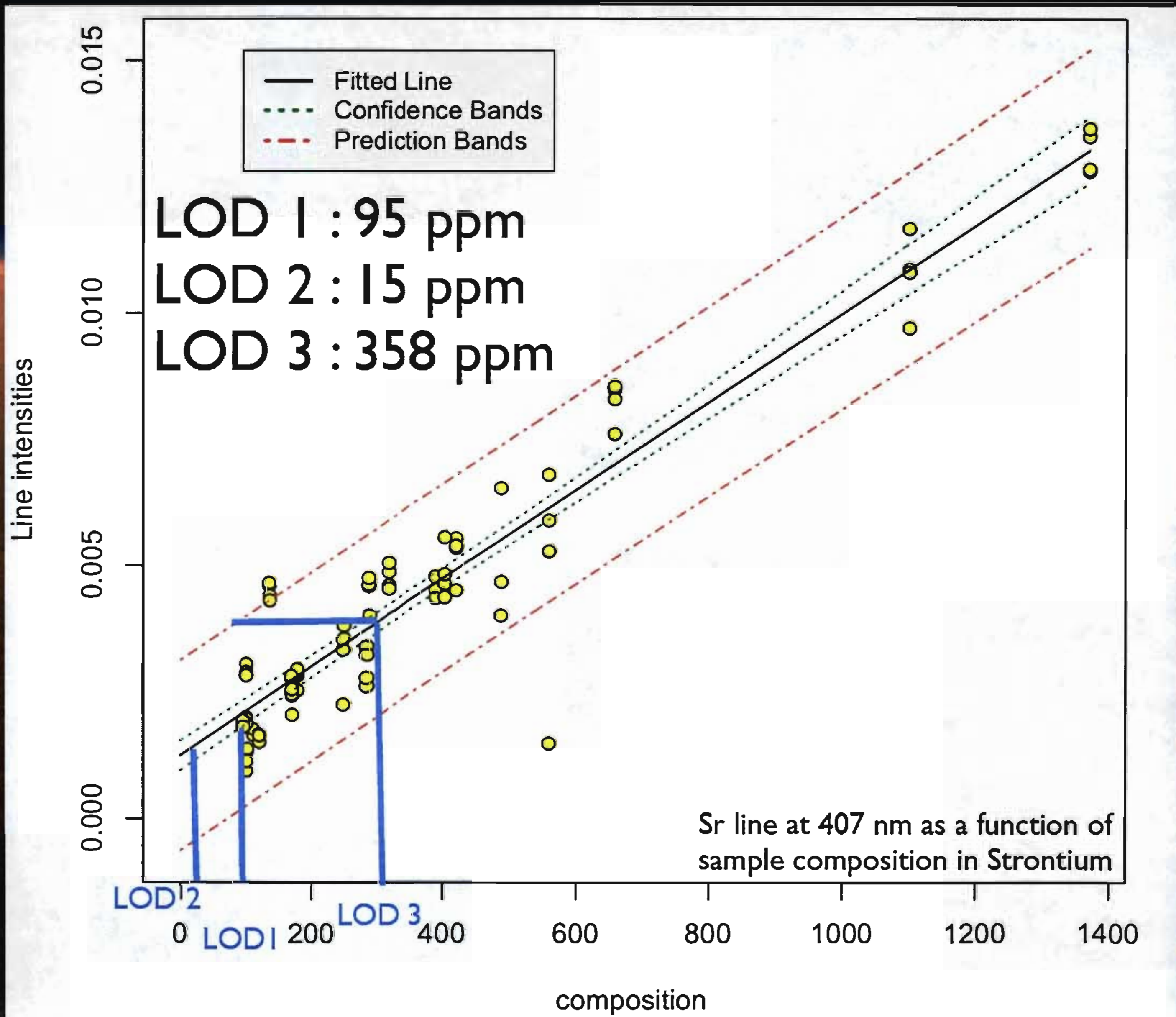


Sr line at 407 nm as a function of sample composition in Strontium

- LOD 1 : First sample with a line "above the noise"
- LOD 2 : Extrapolation of LOD 1 for the lowest concentration
- LOD 3 : Taking into account all the uncertainties

Usually : LOD 2 < LOD1 < LOD 3

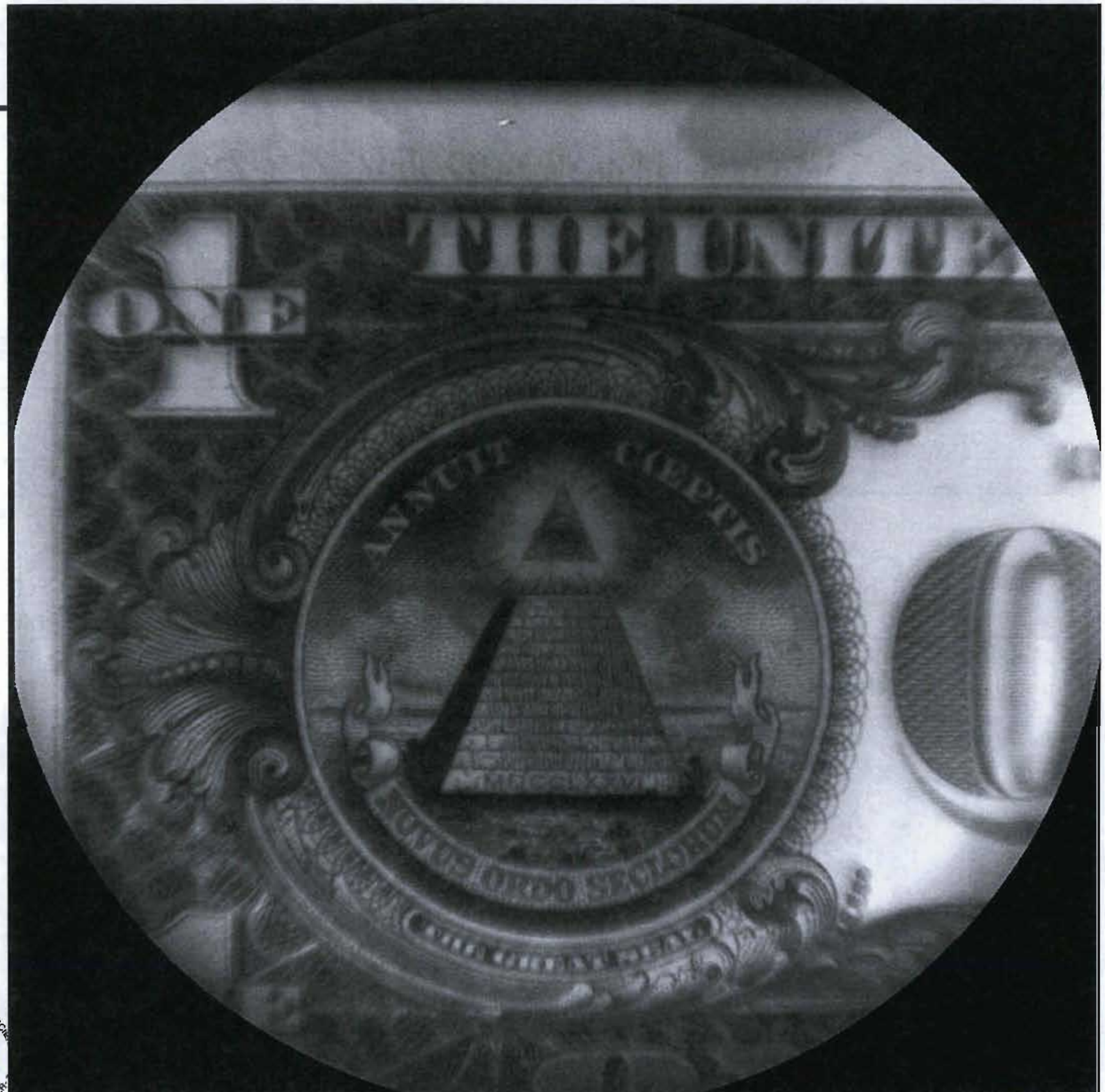
LIMITS OF DETECTION



LIMITS OF DETECTION FIRST RESULTS

Element	λ (nm)	LOD1 (name of the sample)	LOD2	LOD3	Correlation	Limitation of high composition and comments
Cr I	425	360 (BE-N)	9.7	445	0.58	compositions < 500 ppm only
Ba II	455	208 (JB-2)	45	1245	0.70	without STDS-1 (outsider)
Ba I	455	208 (JB-2)	46	973	0.82	without STDS-1
H I	656	503 (Ultramafic)	320	4966	0.75	
K I	766	16 (JDO-1)	58	13843	0.94	
K I	766	16 (JDO-1)	13	12401	0.95	polynomial correction
K I	770	16 (JDO-1)	97	14913	0.93	No
K I	770	16 (JDO-1)	12	12195	0.95	polynomial correction
Li I	671	5 (BHVO-2)	0.3	25	0.98	compositions < 151 ppm only
Mn I	403	303 (NAu2-MID-S)	63	1330	0.90	No
Mn II	294	267 (Green-Rvr)	65	1465	0.88	No
Rb I	780	30 (STSD-1)	11	42	0.94	compositions < 170 ppm only
Sr II	407	95 (NAu2-MID-S)	15	358	0.95	compositions < 1800 ppm only

ChemCam Micro-Imager Performance



$1 @ 3 m distance

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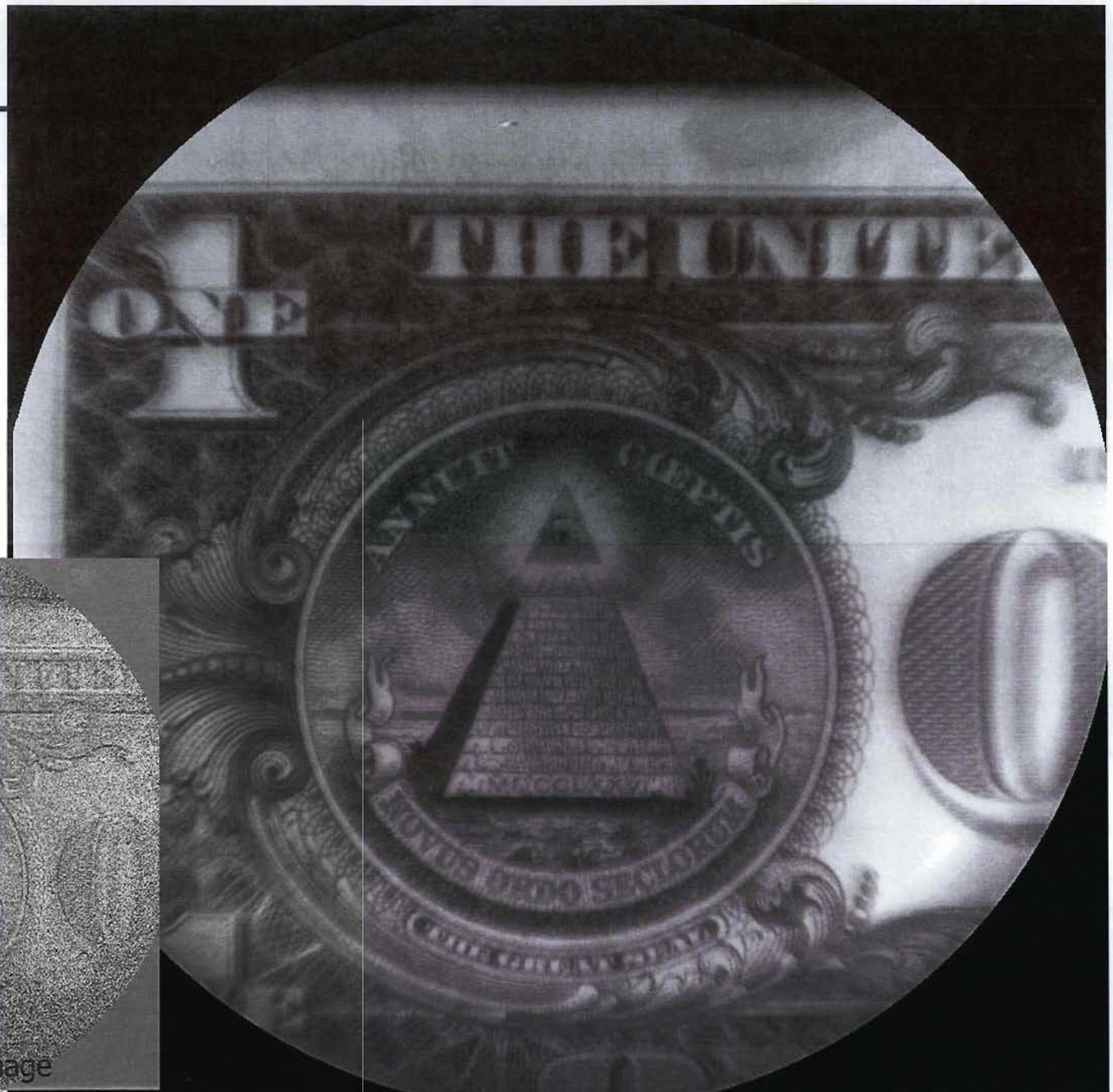
ChemCam Micro-Imager Performance



Stretched Difference Image

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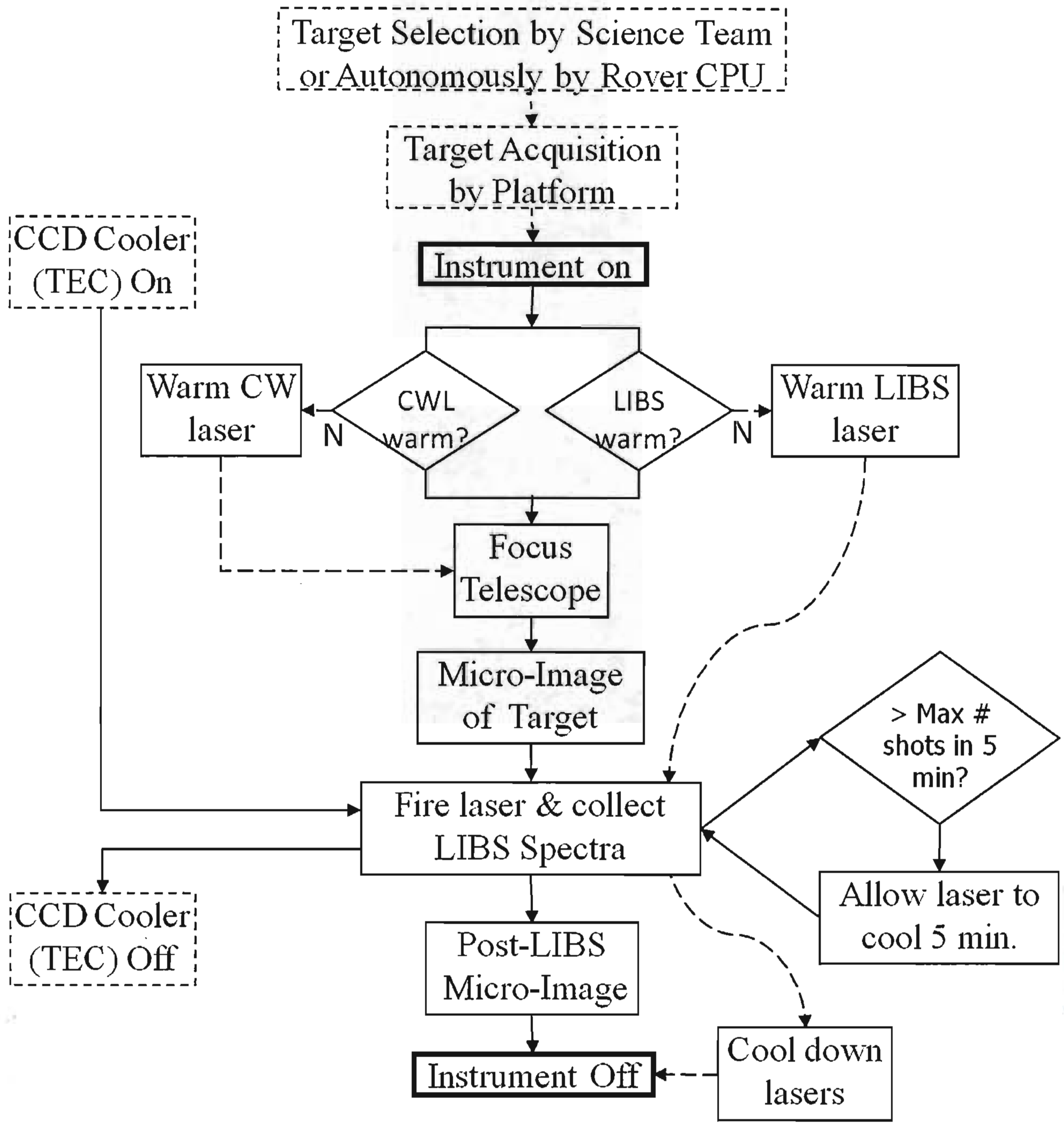
Typical analysis sequence

6 Minutes,
2 W-hr
Per Typical
Analysis



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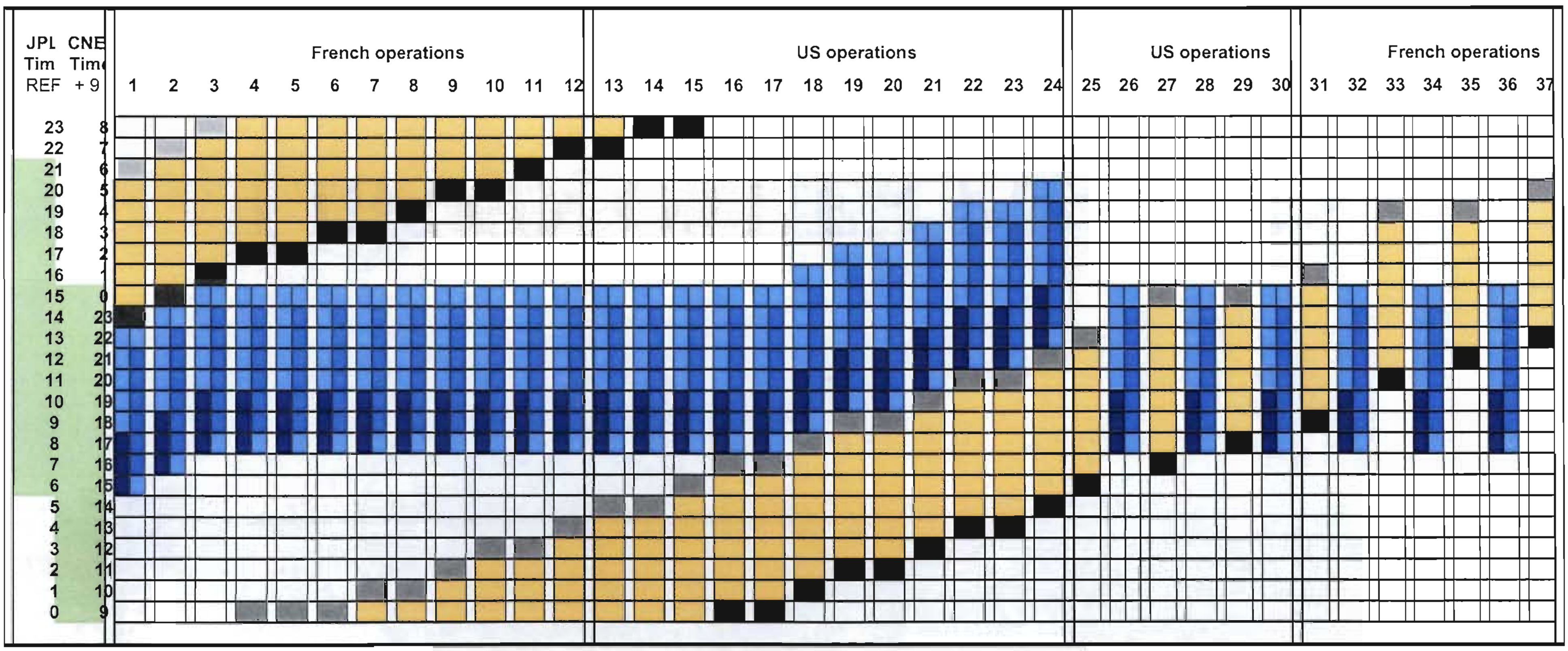
Operations

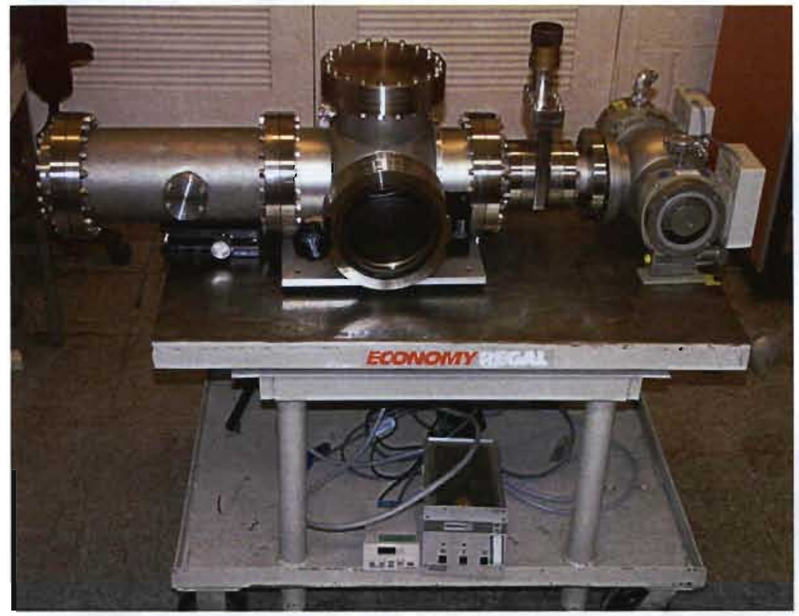
- First 90 days: Operate at Jet Propulsion Laboratory, on Mars time (24 hr, 38 minute days)
- After that, operate from home. Operate ½ from France, ½ from US
- One uplink per day. The rover must be autonomous each day



LIBS ON OTHER PLANETS

Lunar LIBS Experiment

- LIBS sparks are weaker in vacuum (see below)
- Data were taken at 3.5 m
- Laser energies 17-50 mJ
- Samples: lunar simulants and water ice (lunar poles)
- Performed multivariate analyses




~4e-4 Torr


~5 Torr

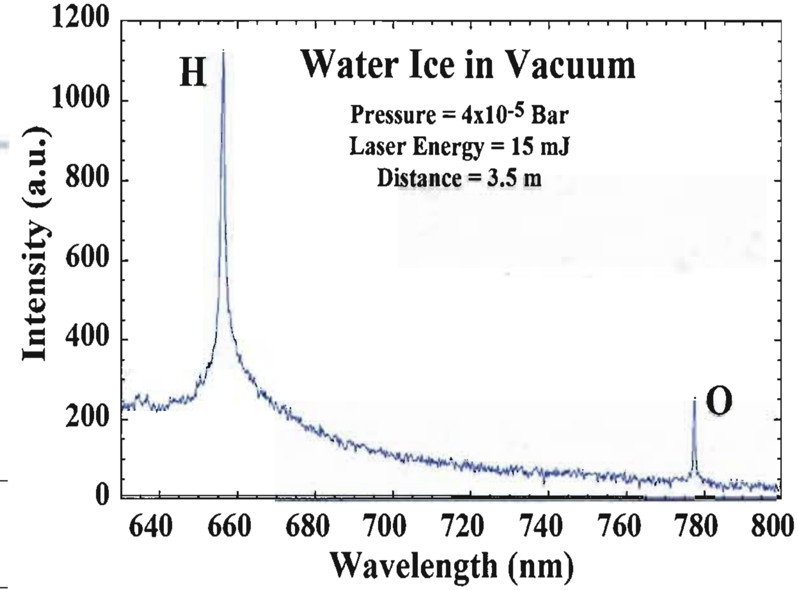

~17 Torr

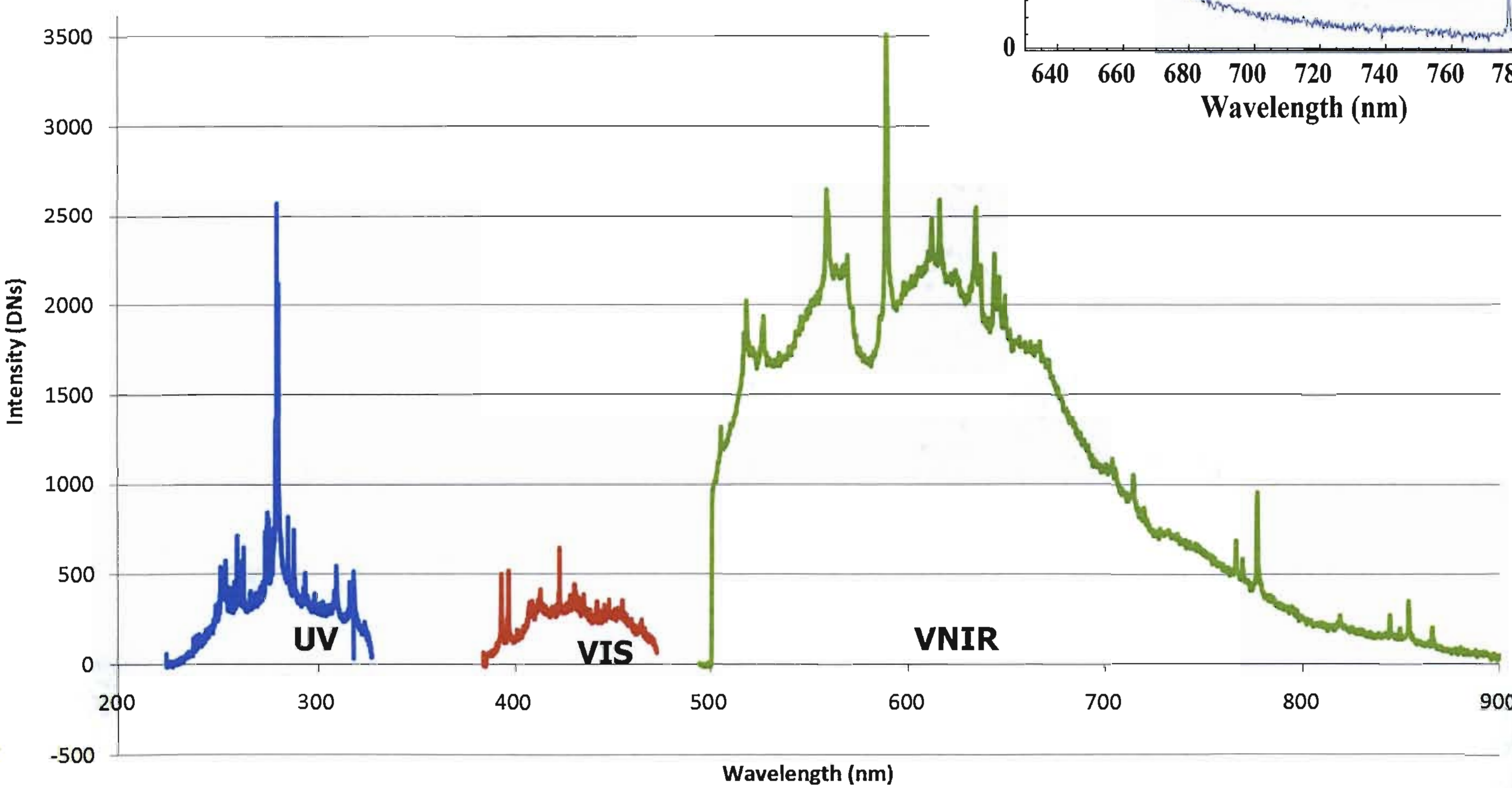

~60 Torr


~585 Torr

Lunar LIBS Spectra

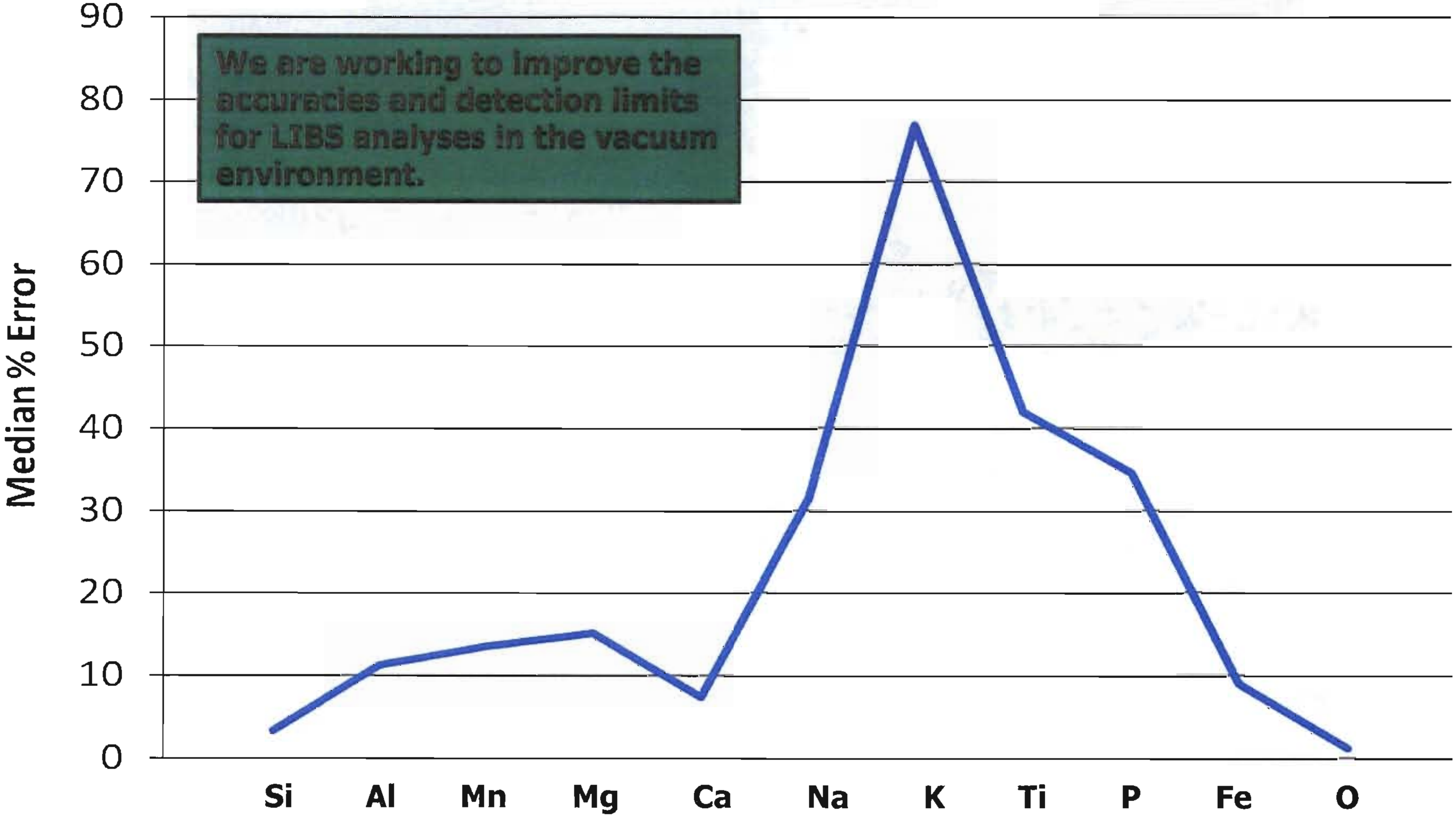
- Significant Bremstrahlung
- Weaker Peaks





Vacuum LIBS Accuracies

17 mJ
3.5 m



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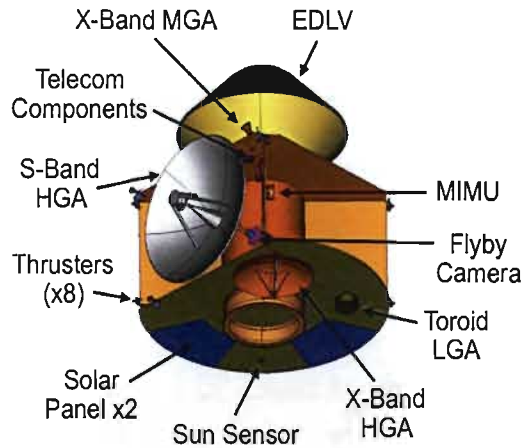
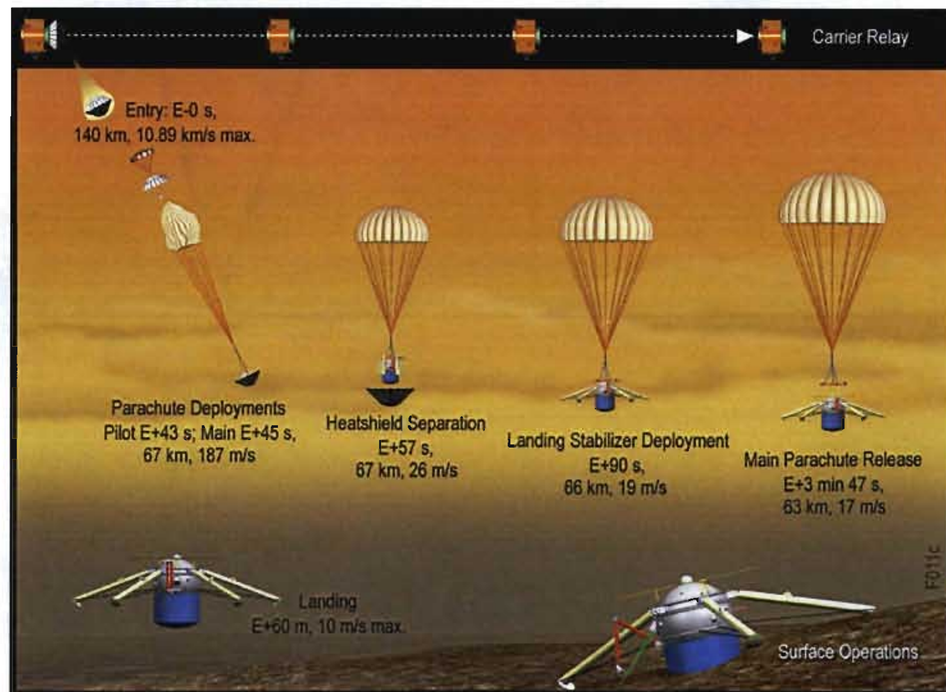
Venus Mission: SAGE*

- *Surface and Atmosphere Geochemical Observer
- May be selected next year for 2016 launch
- 3 hour surface mission, acquire high-resolution panoramic & microscopic images while performing unique elemental & mineralogical observations of the surface & subsurface.
- Instruments:
  - 3 cameras (flyby, descent & panoramic, microscopic),
  - atmospheric structure investigation,
  - 2 gas spectrometers (neutral mass, tunable laser),
  - Raman + LIBS instrument,
  - neutron-activated gamma-ray spectroscopy

CARRIER



LANDER



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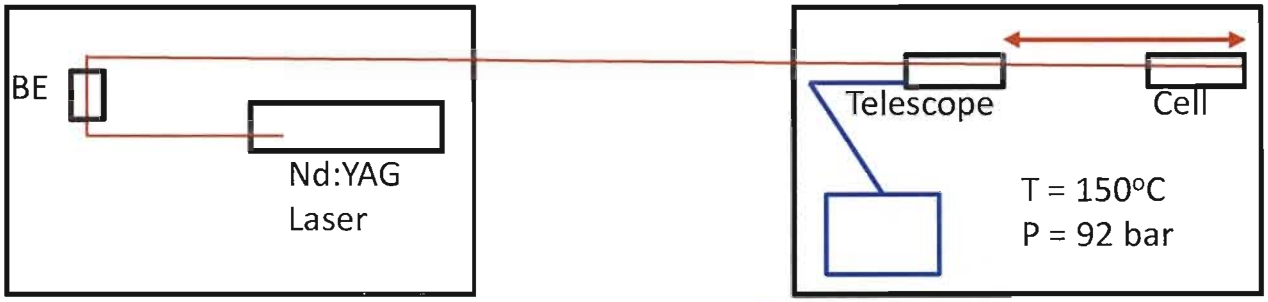
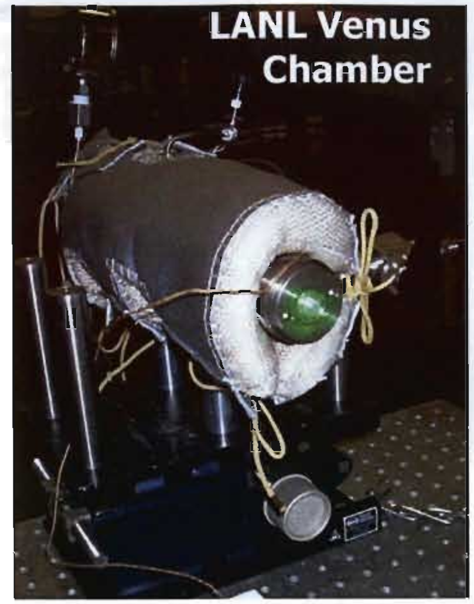
The LIBS Experiment

1.97m
Telescope to sample



1 laser, single pulse
~80mJ/pulse

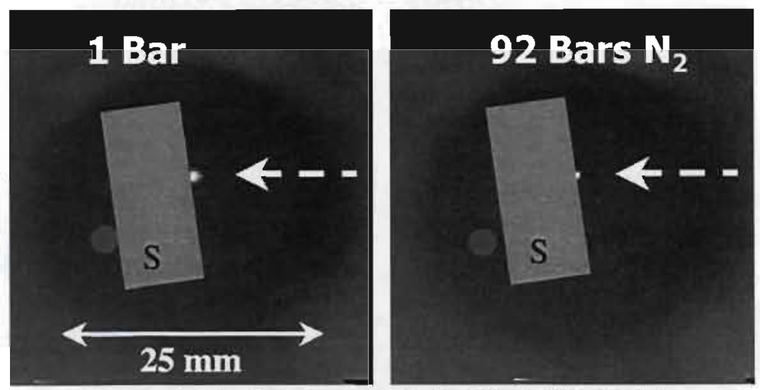
Spectrometers
with ICCDs



Stable LIBS Spots

10 mm

Plasma Spatial Extent



Arp et al. Spectrochim B. 59, 987, 2004.

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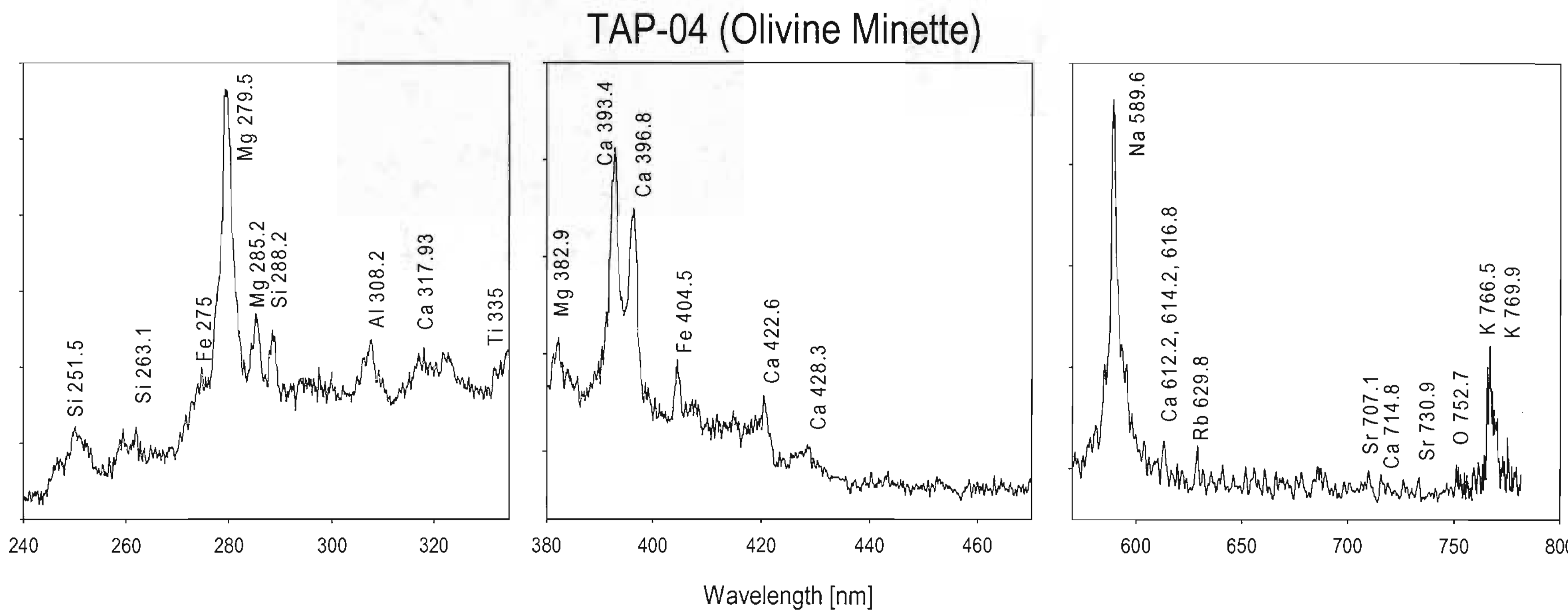
LIBS Spectra



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