Coronal Science from TRACE

Leon Golub, SAO

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The SAO Solar-Stellar X-ray Group

- Leon Golub
- Jay Bookbinder
- Ed DeLuca
- Kathy Reeves
- Steve Saar
- Harry Warren
- Amy Winebarger (now at NRL)
- Joe Boyd, Paul Hamilton, Dan Seaton
The Major Coronal Physics Problems

1. Why is the corona hot?
2. Why is the corona structured?
3. Why is the corona dynamic & unstable?

→Emergence of $B$ into the atmosphere, and response to $B$.

Why Use X-rays to Observe Corona?
Response to flux emergence

1. Vigorous EFR Dynamics.
2. Large-scale B adjustment.
3. Strong local heating.

Outline of Talk

1. Coronal Heating: The New View From TRACE
2. Coronal Structure: Relation of $B$ to X-ray Corona
3. Flares: What TRACE Has Added
4. CMEs
5. What Next?
Heating & Dynamics in ARs

TRACE sees at least four distinct processes in active regions:
1. Steady heating of hot loops (moss).
2. Transient loop brightenings in emerging flux areas.
3. Flare-like events at QSLs.
4. Steady outflows in long, cool structures.

Examples of all four phenomena
TRACE Active Region Observations are not Consistent With Hydrostatic Model

The Real Sun
observed by TRACE in 171 Å
1999 Nov 6, 22:05 UT

The Theoretical Sun
How the Sun would look like if it were in hydrostatic equilibrium

Loops are ubiquitous

Dr. Leon Golub, SAO (ITP Solar Magnetism Program 3/4/02)
Active Region 8536

SUMER Velocities

Dr. Leon Golub, SAO (ITP Solar Magnetism Program 3/4/02)
Coronal Science from TRACE

Static vs. Flow Model

Best fit vs. Uniform heating
How monochromatic are these loops?

Microscale B vs. X

1. Complex relation between photosphere and corona.
2. Very rapid dynamics.
3. Large T-range to be observed.

Resolution requires Solar-B observations!
TRACE Flare Results

- TRACE observes Fe XXIV 192 Å – highest resolution images ever of hot flare plasma
- Qualitatively consistent with flare models – hot loops form first, cool post-flare loops form later
- Evidence for “hot” regions – 20 MK plasma is found above 10 MK flare arcades
- Fine structure in flares – simulations with many small loops are needed to reproduce the observations
- Pre-Flare observations – evolution of ribbon brightenings is complex

A Typical Event
Flares & CMEs

1. Initial energy release along current sheet ("spotty")
2. Spreading of ribbons vs. height of high-T (see next slide).

A Model for Flare Transition Region Evolution


Flare loop evolution has three phases: heating, conduction-dominated cooling, and radiation-dominated cooling. Model of TRACE Emission:

- Standard 1D loop.
- Underlying heating and/or conduction-driven evaporative cooling
- Assume radiative losses and gravity are negligible, motions are slow (compared to sound speed), and heating is spatially uniform ($\propto \tau(t)$).

The DSM is given by:

$$\tau(t) = \frac{N^2 \pi L}{2} \sqrt{\frac{3}{2}} \frac{\pi^2}{\rho \sqrt{\mu^2 - \rho^2}}$$

where

$$\Theta(v) = \pi \Theta(v) \left( \frac{\pi}{2} \int_0^\infty \frac{\Theta(v) \, dv}{\pi} \right)^{-\frac{3}{2}}$$

and $p(v) = \rho(0) + \frac{1}{2} \int_0^v \Theta(v) \, dv$.

Given any assumed form for the heating $\Theta(t)$, we determine the time dependence of the DSM. We can, in principle, infer $\Theta(t)$ from the observed form of $\tau(t)$.
Consider two simple cases:
a) Pure evaporative cooling $e(t) = 0$, and
b) Constant heating, $e(t) = \text{const.}$

Pure cooling:
\[
\tau \approx N_i^2 L_i \left( \frac{T_i}{T_M} \right)^{5/2} \frac{(1 + t/t_i)^{3/2}}{\sqrt{1 - (\theta_M/\theta)^{3/2}}} 
\]  
(3)

During the time when TRACE sent footpoint emission only, evaporative cooling would produce emission with an almost linear temporal variation,

\[
\tau = \tau_i(1 + t/t_i)^{3/2}. 
\]

Constant heating:

Time dependence of temperature $\theta(t)$ is:

\[
\theta(t) = \theta_i(1 + (C_i/t_i)(e^{\theta_i/\theta_i} - 1))^{-3/2}, 
\]

TRACE emission measure is roughly quadratic with time:

\[
\tau = \tau_i(1 + t/t_i)^2. 
\]

Comparison: Evaporative Model vs. TRACE Obs.
July 25, 1999 M2.4 Limb Flare

Most of the Flare Emission is Near 10 MK: June 25, 1999 M2.4
SXT and TRACE Show 15-20 MK Loop-Top Plasma

March 24, 2000 X1.8 Flare: 1600 Å and 195 Å Movies
March 24, 2000 X1.8 Flare: 195 Å Near SXR Peak

March 24, 2000 X1.8 Flare: 195/171 Filter Ratios
Reconnection at top of flares

1. Flare heating is preceded by expansion of high loops.

2. Hi-T source above postflare loops.

3. Hi-T coincident with footpoint ribbon heating.

4. Source moves upward during course of flare.

Modeling the Evolution of the Flare Arcade (2D)
Comparisons With Simulation: TRACE 195/171 Filter Ratios

Improved Fit with Taller Loops
March 17, 2000 M1.1: TRACE 1600 Å Movie

March 17, 2000 M1.1: TRACE 1600 Å Images
March 17, 2000 M1.1: TRACE 1600 Å Light Curves

TRACE Footpoint vs. BATSE HXR
The Solar-B Mission

The Solar-B Instrument Complement

1. Solar Optical Telescope with Focal Plane Package (FPP)
   - 0.5m Cassegrain, 480-650nm
   - VMG, Spectrograph
   - FOV 164X164 arcsec

2. EUV Imaging Spectrograph (EIS)
   - Stigmatic, 180-204, 240-290Å
   - FOV 6.0X8.5 arcmin

3. X-ray Telescope (XRT)
   - 2-60Å
   - 1 arcsec pixel
   - FOV 34X34 arcmin
XRT vs. SXT Comparison

1. Higher spatial resolution: 1.0” vs. 2.5”
2. Higher data rate: 512kB continuous.
3. Ten focal plane analysis filters.
4. Extended low-T and high-T response.
5. FIFO buffer for flare-mode obs.

Solar-B XRT Flight Design
Response to flux emergence

The observational problem:
1. Vigorous EFR Dynamics.
2. Large-scale B adjustment.
3. Strong local heating.

How are Solar-B Instruments to be Targeted?

Solar-B Observations

Full Sun or AR-belt X-ray obs, high cadence for extended time period.

Ground-based full Sun coordinated obs.

Q: How do we target FPIP and EIS to the regions of interest?
From Photosphere to Corona

1. Choose target of interest.

2. Surface B from FPIP.

3. Photospheric and chromospheric structure at high spatial and temporal resolution (FPIP/EIS).


5. Coronal structure and dynamics (XRT).

Flares & CMEs

1. Initial energy release along current sheet (“spotty”)

2. Spreading of ribbons vs. height of high-T (see next slide).
Solar-B Flare Obs

Solar-B is launched near minimum of cycle.

Flare observations require difficult coordinated observations: FPP for B, EIS for T, XRT for geometry and context.

Recommendation: Do not attempt flare program at start of mission. (But be prepared to deal with flares when they occur.)

XRT Observing Wish List

Question: What observations would you forever regret not having done?

(Note: We ignore for a moment whether or not there practical difficulties in doing these observing programs.)
## Full Corona Survey

One full Solar rotation:

1. Full Sun, full resolution.
2. Cadence at least twice per orbit.
3. Two or more filters for analysis.

## Coronal dynamics survey

One day of high time resolution, large-field coronal observation.

1. Image cadence at least every 20 seconds.
2. F.O.V. at least 512x512 arcsec, centered on chosen target.
3. At least two analysis filters, for disk passage.
Evolution of Eruptions

1. Where do eruptive structures (e.g. sigmoids) come from?

2. Follow evolution of several ARs for entire disk passage at moderate cadence with XRT, using at least three analysis filters.

3. Map vector $\mathbf{B}$ in and around the region.

3a. Map multi-thermal TR and corona in and around the region.

Eruptions - Observing Program

1. Requires at least 16X16 arcmin box, in at least two analysis filters.

2. Requires several months observation at 2/day cadence full Sun, plus at least twice per orbit on target region for several days.

3. Will have to be done many times throughout mission - recommend at least twice during first 3 months of observations.
## Requirements Flowdown

<table>
<thead>
<tr>
<th>Primary Requirements</th>
<th>Definition</th>
<th>Value</th>
<th>Primary Hardware</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Time</td>
<td>Shutter open/close</td>
<td>4ms (min) 10 sec (max)</td>
<td>Shutter, Filters, GI mirror effective area</td>
</tr>
<tr>
<td>Cadence</td>
<td>Time between exp.</td>
<td>2 sec</td>
<td>Shutter, Filter wheels</td>
</tr>
<tr>
<td>Temp. Range</td>
<td>Temp. range</td>
<td>6.1 &lt; log T &lt; 7.5</td>
<td>GI Coatings, Filters</td>
</tr>
<tr>
<td>Temp. Resolution</td>
<td>Temp. discrimination</td>
<td>Log T = 0.2</td>
<td>Filter selection</td>
</tr>
<tr>
<td>Image Resolution</td>
<td>50% encircled energy</td>
<td>2&quot; at 0.5 keV on axis</td>
<td>GI Mirror Prescription</td>
</tr>
<tr>
<td>Field of View</td>
<td>Angular coverage</td>
<td>&gt;30 arcmin</td>
<td>GI Mirror Prescription</td>
</tr>
<tr>
<td>GI to VLI alignment</td>
<td>Align X-ray to WL images</td>
<td>10 arcsec</td>
<td>Mirror Assembly</td>
</tr>
<tr>
<td>GI to [EIS,SOT] alignment</td>
<td>Align XRT to other instruments</td>
<td>1 arcmin</td>
<td>XRT structure</td>
</tr>
</tbody>
</table>

**Derived Requirements**

| Visible Light Rejection      | Reduction of solar visible light at focal plane | >10**11                   | Prefilters, FP filters, structures          |

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**What Next?**

**RAM: A Solar Microscopy Mission**

(Reconnection And Microscale Probe)
Science Objectives

- Understand the dynamics of solar & astrophysical plasmas
  - image the structures of unstable plasma configurations
  - image the onset & evolution of plasma instabilities

- Understand the energetics of magnetically heated plasmas

- Understand the fine-scale structure of astrophysical objects from planets to quasars.
  
  RAM uses the Sun, solar system objects and galactic X-ray sources as laboratories for testing and extending our knowledge of astrophysical plasmas.

Comparative Resolutions

<table>
<thead>
<tr>
<th>EIT/SXT image</th>
<th>TRACE resolution</th>
<th>RAM simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global dynamics</td>
<td>Coronal/Photospheric connections</td>
<td>Microstructure Dynamical processes Plasma physics</td>
</tr>
</tbody>
</table>

Comparative Fields of View

EIT/SXT F.O.V.
Solar-B F.O.V.

TRACE F.O.V.

RAM HIRES F.O.V.

Deployed RAM Configuration

INSTRUMENT/PRIMARY MIRROR BAYS
Soft X-ray Imager/Bolometer

EXTENDABLE OPTICAL BENCH

PRE-FILTER VACUUM CHAMBER

SPACECRAFT

EUV Imaging Spectrometer
Science Themes

- Plasma Dynamics
- Thermal Structure and Stability
- The Onset of Large Scale Instabilities
- Non-Solar Objects

Plasma Dynamics

- Reconnection
  - loop-loop interaction
  - flux emergence
  - nano-flares
  - AR jets
  - macro-spicular jets
  - filament eruption
Plasma Dynamics

- Waves
  - origin of high speed wind
  - tube waves
  - coronal seismology

Figures from Nakariakov et al. (1999): decaying loop oscillations seen in TRACE can be used to estimate the coronal dissipation coefficient.

\[ R_e \sim 6 \times 10^5 \text{ or } R_m \sim 3 \times 10^5, \text{ about 8 orders of magnitude less than classical values.} \]

Thermal Structure/Stability

- Physical Properties
  - \( T_e, n_e, \text{EM} \)
  - energetics
  - variability timescales
- Multithermal Structure
  - steady loops
  - filaments
Onset of Large Scale Instabilities

- Emerging Flux Region
  - twisting/untwisting
  - reconnection
- delta Spots
  - current sheets
  - topology changes
- Active Filaments
  - $Te, ne$
  - local heating

Non-Solar Objects

- Jupiter
  - S VII @ 198
- Nearby RS CVns
- Galaxy Cluster Halos
- Comets
- Any EUVE source within 1 deg of Sun
### Science Drivers I: Spatial Scales

<table>
<thead>
<tr>
<th>Category</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Global” MHD Scales</td>
<td>$10^5$ km</td>
</tr>
<tr>
<td>Active Regions; granulation scales</td>
<td>$10^3$ km</td>
</tr>
<tr>
<td>Transverse scales</td>
<td>$10^1 - 10^3$ km</td>
</tr>
<tr>
<td>$\delta T$, $\delta n$</td>
<td>$&lt;10$ km</td>
</tr>
<tr>
<td>$\delta B_\perp$ and $j$</td>
<td></td>
</tr>
<tr>
<td>Reconnection sites</td>
<td>$&lt;10$ km</td>
</tr>
<tr>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td></td>
</tr>
<tr>
<td>Dynamics</td>
<td></td>
</tr>
</tbody>
</table>

### Science Drivers II: Time Scales

<table>
<thead>
<tr>
<th>Category</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Alfven time</td>
<td>~10 sec</td>
</tr>
<tr>
<td>Sound speed vs. loop length</td>
<td>~100 sec</td>
</tr>
<tr>
<td>Ion formation times</td>
<td>~1 - 10 sec</td>
</tr>
<tr>
<td>Plasma instability times</td>
<td>~10 - 100 sec</td>
</tr>
<tr>
<td>Transverse motions</td>
<td>1 - 100 sec</td>
</tr>
<tr>
<td>Surface B evolution times</td>
<td>minutes - months</td>
</tr>
</tbody>
</table>
**Current Instrument Complement**

- RAM has an EUV imaging instrument:
  - A High Resolution Telescope - 0.01 arcsecond pixels, >arcminute FOV.
- RAM has an EUV spectrograph:
  - SERTS- or SUMER-like spectrograph, w/improved optics and gratings for 0.5” performance
- RAM has an X-ray calorimeter, for imaging spectroscopy at X-ray wavelengths.
- RAM has a TRACE-like EUV context imager.

**Instrument Sensitivity I**

<table>
<thead>
<tr>
<th>Item</th>
<th>TRACE (195A)</th>
<th>HIRES (193A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric Area (cm²):</td>
<td>162</td>
<td>3,850</td>
</tr>
<tr>
<td>Reflectivity (2 bounces)</td>
<td>0.12</td>
<td>0.25</td>
</tr>
<tr>
<td>CCD QE</td>
<td>0.08</td>
<td>0.8</td>
</tr>
<tr>
<td>Throughput Ratio (HIRES/TRACE)</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.5”</td>
<td>0.02”</td>
</tr>
<tr>
<td>Pixel Area ratio:</td>
<td>1</td>
<td>1.6 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 x10⁻⁴</td>
</tr>
</tbody>
</table>
### Instrument Sensitivity II

**EXPOSURE TIMES**

<table>
<thead>
<tr>
<th>Item</th>
<th>TRACE (195A)</th>
<th>HIRES (193A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst Case:</td>
<td>10sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>(no substructure)</td>
<td></td>
<td>40 sec</td>
</tr>
<tr>
<td>Best Case:</td>
<td>10sec</td>
<td>0.005 sec</td>
</tr>
<tr>
<td>(all flux in one pixel)</td>
<td></td>
<td>0.02 sec</td>
</tr>
<tr>
<td>Nominal Case:</td>
<td>10sec</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>(flux “thread”)</td>
<td></td>
<td>1 sec</td>
</tr>
</tbody>
</table>

### Instrument Details

<table>
<thead>
<tr>
<th>Item</th>
<th>High-Resolution Imager</th>
<th>Context Imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Diameter</td>
<td>0.75m</td>
<td>0.3m</td>
</tr>
<tr>
<td>Eff. Focal Length</td>
<td>240m</td>
<td>5m</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.01”</td>
<td>0.25”</td>
</tr>
<tr>
<td>CCD Format</td>
<td>6k x 8k</td>
<td>4k x 4k</td>
</tr>
<tr>
<td>F.O.V</td>
<td>60”x80”</td>
<td>16’ x 16’</td>
</tr>
</tbody>
</table>
Coronal Science from TRACE

Requirements Flow Down

Primary Science Goals
- Understand the dynamics of solar & astrophysical plasmas
- Understand the energetics of magnetically heated plasmas

Measurement Capabilities
- Minimum effective area: 450 square cm.
- Telescope Angular Resolution (pixel): 0.01 – 0.2 arcsec
- Fields of View: 40” to full sun
- Minimum Time Resolution: 0.05 seconds
- Cadence: 0.2 – 5 seconds

“Build to cost” cost is a design constraint

Engineering Implications
- Telescope Angular Resolution:
  - 27m Optical Bench
  - Superb figure/finish on optics
  - In-orbit focus/alignment
  - Image stabilization system
  - Tight thermal control on mirror assemblies
  - Other errors kept small compared to mirror
- Field of View:
  - Two telescope systems
- Bandpass & Resolving Power:
  - Multilayer coatings

Key Technologies
- High Throughput Optics
  - High performance multilayer coatings
- High Spatial Resolution:
  - Ultra precision optics
  - Extendable optical bench
  - Engineered multilayers
- High Spectral Resolution:
  - Large array bolometers

RAM uses a combination of innovative and proven technologies to yield exciting new science:

- **New Technologies:**
  - Ultra-high precision optics (0.25m pathfinder mirror under development with partners ROSI and Bauer, Assoc.).
  - Cryogenic bolometers for soft x-ray spectroscopy.

- **Heritage technologies:**
  - Extendable Optical Bench: RAM re-uses the SRTM deployable mast to reduce cost, reduce risk, & improve reliability.
  - Image stabilization techniques: RAM extends techniques from TRACE and SOHO/MDI missions.
  - Multilayers based on TRACE heritage

Dr. Leon Golub, SAO (ITP Solar Magnetism Program 3/4/02)
## Ultra-Precision Optics

<table>
<thead>
<tr>
<th></th>
<th>HIRES Requirements</th>
<th>Commercial Goals</th>
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<tbody>
<tr>
<td>Figure error</td>
<td>&lt;0.4 nm rms</td>
<td>0.25 nm rms</td>
</tr>
<tr>
<td>Mid-frequency Error</td>
<td>&lt;0.5 nm rms</td>
<td>0.2 nm rms</td>
</tr>
<tr>
<td>Microroughness</td>
<td>&lt;0.3 nm rms</td>
<td>0.1 nm rms</td>
</tr>
</tbody>
</table>

### Optics Metric

![Optics Metric Graph](image)

- Normal Incidence
- Early Keck
- NEXT
- MSSTA
- AXAF
- TRACE
- Lab Demo
- HIREX
Extendable Optical Bench Prototype

Mission Summary
Current Baseline

<table>
<thead>
<tr>
<th>Class</th>
<th>ST Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit:</td>
<td>L1</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>3 year/5 year</td>
</tr>
<tr>
<td>Launch Date</td>
<td>&gt;2007</td>
</tr>
<tr>
<td>Data Downlink</td>
<td>&gt;1500 images/day</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Delta-III medium</td>
</tr>
<tr>
<td>Ground Station</td>
<td>continuous</td>
</tr>
<tr>
<td>Instrument</td>
<td></td>
</tr>
<tr>
<td>Complement</td>
<td>HRI/CT/SoCCS/XRB</td>
</tr>
</tbody>
</table>
Launch Configuration

- Mass (S/C): 446 kg (with reserve)
- Mass (total): 1452 kg
- Mass Margin: 23%
- Power: 1410 watt EOL
- Power Margin: 24.2%
- Telemetry: 50Mbps (X-band)
- On-board Storage: 40 Gbyte
- Attitude: 3-axis stabilized
- Stability: 20”, 3-σ, t<100s

Study Team Members

- SAO
- Lockheed-Martin
- NASA/GSFC
- NSO
- Univ. of Chicago
- ROSI
- Bauer Assoc.
- University of Tokyo
- Obs. de Paris, Meudon
- MPIAe
- Osserv. Astron. di Palermo
- Univ. of St. Andrews
End

Historical Context

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Resolution</th>
<th>F.O.V</th>
<th>Wavelength Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIXT</td>
<td>0.6”</td>
<td>full Sun</td>
<td>one line</td>
</tr>
<tr>
<td>YOHKOH</td>
<td>2.5”</td>
<td>full Sun</td>
<td>filters</td>
</tr>
<tr>
<td>SoHO</td>
<td>2.5”</td>
<td>full Sun</td>
<td>four lines</td>
</tr>
<tr>
<td>TRACE</td>
<td>0.5”</td>
<td>8.5’</td>
<td>three lines</td>
</tr>
<tr>
<td>Solar-B</td>
<td>1.0”</td>
<td>full Sun</td>
<td>Filters</td>
</tr>
<tr>
<td>Solar Probe</td>
<td>0.03”*</td>
<td>30”*</td>
<td>one line</td>
</tr>
<tr>
<td>HIREX</td>
<td>0.01,0.25</td>
<td>40”, 16’</td>
<td>One line</td>
</tr>
</tbody>
</table>
Solar-B Observations

Full Sun or AR-belt X-ray obs, high cadence for extended time period.

Ground-based full Sun coordinated obs.

Q: How do we target FPIP and EIS to the regions of interest?

Solar-B Flare Obs

Solar-B is launched near minimum of cycle.

Flare observations require difficult coordinated observations.

Recommendation: Do not attempt flare program at start of mission. (But be prepared to deal with flares when they occur.)
XRT Observing Wish List

Question: What observations would you forever regret not having done?

(Note: We ignore for a moment whether or not there practical difficulties in doing these observing programs.)

Full Corona Survey

One full Solar rotation:

1. Full Sun, full resolution.

2. Cadence at least twice per orbit.

3. Two or more filters for analysis.
Coronal dynamics survey

One day of high time resolution, large-field coronal observation.

1. Image cadence at least every 20 seconds.

2. F.O.V. at least 512x512 arcsec, centered on chosen target.

3. At least two analysis filters, for disk passage.

Evolution of Eruptions

1. Where do eruptive structures (e.g. sigmoids) come from?

2. Follow evolution of several ARs for entire disk passage at moderate cadence with XRT, using at least three analysis filters.

3. Map vector $\mathbf{B}$ in and around the region.

3a. Map multi-thermal TR and corona in and around the region.
Eruptions - Observing Program

1. Requires at least 16X16 arcmin box, in at least two analysis filters.

2. Requires several months observation at 2/day cadence full Sun, plus at least twice per orbit on target region for several days.

3. Will have to be done many times throughout mission - recommend at least twice during first 3 months of observations.