Designing for situation awareness and operator control with large data volumes in NASA's Deep Space Network

Alexandra Holloway
“From the Desert to the Stars”
DSN provides support to most of the world’s spacecraft.
<table>
<thead>
<tr>
<th>Deep Space Network</th>
<th>Staffing</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Antennas</td>
<td>3–6 Operators per shift</td>
</tr>
<tr>
<td>3 Sites</td>
<td>2 Links per operator</td>
</tr>
<tr>
<td>50 Years old</td>
<td>3 8-hour shifts per station</td>
</tr>
<tr>
<td>37 hour Round-trip light time</td>
<td>24 Hours per day</td>
</tr>
</tbody>
</table>
Two links per operator
Following the sun
Human problems in “big” data
Q: What should I pay attention to?

A: Only the things that need it.
Task Action Sequence, Basic

Diagram showing the sequence of goals, intention, expectation, evaluation, action specification, execution, interpretation, perception, and physical activity. The diagram is based on Norman (1986).
Task Action Sequence, Expert

Berkman (2009)
Task Action Sequence, Expert

Berkman (2009)
Situation Awareness

Perception of elements in current situation
Level 1

Comprehension of current situation
Level 2

Projection of future states
Level 3

Endsley (1995)
SITUATION AWARENESS

Perception of elements in current situation → Comprehension of current situation → Projection of future states → Decision → Performance of actions

Level 1

Level 2

Level 3

* System capability
* Interface design
* Stress & workload
* Complexity
* Automation

* Goals & objectives
* Preconceptions (expectations)

* Information processing mechanisms
* Long-term memory store
* Automaticity

* Abilities
* Experiences
* Training
8 Things That Help Situation Awareness

- Decreasing workload, fatigue, anxiety
  Verify necessary support documents and equipment
  Step 1

- Not relying on short-term memory alone
  Verify necessary support documents and equipment
  Step 1

- Misplaced salience
  Verify necessary support documents and equipment
  Step 1

- Out of the loop
  Verify necessary support documents and equipment
  Step 1

- Support correct mental models
  Verify necessary support documents and equipment
  Step 1

- Watch for data overload
  Verify necessary support documents and equipment
  Step 1

- Complexity
  Verify necessary support documents and equipment
  Step 1
Where do we add autonomy?

Where?
Raising SA in an autonomous world

Levels of automation
Adaptive automation
Design principles
What should I pay attention to?
Goal-oriented task analysis

Endsley (2012)
Goal-oriented task analysis

Goal → Decision → Task → Action

- Perception of elements in current situation (Level 1)
- Comprehension of current situation (Level 2)
- Projection of future states (Level 3)

Endsley (2012)
Link control operator goals

Allocate resources
Set up and ensure proper working order of equipment for support activities
Goal 1

Coordinate activities
Work with maintenance and test crews
Goal 3

Report and verify
Ensure and assist discrepancy reporting
Goal 4

Operate and troubleshoot
Ensure supports are handled according to project instructions; prevent and respond to anomalies
Goal 2

Ensure safety
Be up to date on training and aware of surroundings
Goal 5

Holloway (2014)
2.0 Operate and Troubleshoot

2.1 Ensure all support is executed according to briefing and/or documentation.

2.1.1 Ensure all expected outside-of-the-nominal operating parameters are properly executed.
2.1.2 Ensure proper working order of equipment.

2.2 Respond to anomalous conditions or alarms.

2.2.1 Deny fast cause of alarm.
2.2.2 Deny fast impact on data return.

2.2.3 Resolve problem.

2.3 Provide proactive control.

2.3.1 Assess status of adjacent facilities.
2.3.2 Assess status of local facility.
2.3.3 Assess status file structure.

What is the status of other facility?
What is the status of the other tracks at my facility?
Can't prevent alarm from occurring?
What prevent; vs; ons; are needed?

What is the likely cause?
What is the data integrity?
What is the best way to resolve the problem?

Causes:
- Redacted vs expected vs actual
- Equipment anomaly
- Environmental factors

Discuss with project (§?)
Coordinate with maintenance

2014-04-21
Slide 23/MAX
LINK CONTROL OPERATOR
OPERATE AND TROUBLESHOOT
FLOW ANALYSIS

Prepare
Verify necessary support documents and equipment

Pre-cal
Configure, calibrate equipment

In-Track
Provide necessary support

Post-cal
Cool down and stow equipment

Report
Document discrepancies

Step 1
Step 2
Step 3
Step 4
Step 5

Holloway (2013)
Process

User-centered design
Daily engagement of expert link control operators and other ops personnel

Data-driven prototyping
Realness of data contributes to realistic prototypes and richer conversations, even if the prototype is paper

Vision statement
Complex sentence serves as a guiding principle or overarching goal

Hypothesis-led iteration
Each design iteration serves to address a specific hypothesis or open question

Frequent, short “sprints”
Two-week long sprints keep tasks focused; an overarching goal keeps sprints connected to vision
What's been tried
Original displays: One-to-one mapping with hardware
“There’s a billion displays.”

Davidoff (2013)
IRIS displays: too much hierarchy, latency
“What we need is speed.”

Ames (2013)
### Summary

#### Antenna

<table>
<thead>
<tr>
<th>Antenna (AZ, EL)</th>
<th>Subreflector (x, y, z)</th>
<th>Master Equatorial</th>
<th>Conscan</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACKING</td>
<td>TRACKING</td>
<td>STOWING</td>
<td>DISABLED</td>
</tr>
<tr>
<td>123.45, 67.29</td>
<td>-0.0002</td>
<td>-0.0003</td>
<td>0.0000</td>
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</table>

#### Uplink

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Command</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.62 kW</td>
<td>MOD1</td>
<td>TRK</td>
</tr>
</tbody>
</table>

#### Downlink

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Subcarrier</th>
<th>Symbol</th>
<th>Telemetry</th>
<th>D. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>-134.136 dBm</td>
<td>57.101 dB-Hz</td>
<td>3.192 dB</td>
<td>Q/L</td>
<td>WAIT FOR LOCK</td>
</tr>
</tbody>
</table>

### Antenna - AP15 X

#### Antenna

<table>
<thead>
<tr>
<th>RA</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.45</td>
<td>123.45</td>
</tr>
</tbody>
</table>

#### Pred Mode

- DCOS: TRACKING

#### Tracking Mode

- act1

#### WRAP

- THAT'S A WRAP

#### Downlink Band

- X:

#### ENC Model

- 123.45

#### AC1 Model

- xploit.ac1

#### Subreflector

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>RPOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.186 inches</td>
<td>1.764 inches</td>
<td>1.764 inches</td>
<td>240.00 deg</td>
</tr>
</tbody>
</table>

#### Master Equatorial

<table>
<thead>
<tr>
<th>HA</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.123</td>
<td>342.456</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actual</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.123</td>
<td>342.456</td>
</tr>
</tbody>
</table>
In-track >
Operate, troubleshoot
Ensure supports are handled according to project instructions; prevent and respond to anomalies
Goal 2

Context: Monitor
-- Develop, retain awareness of the big picture to prevent and troubleshoot anomalous conditions

Control: Command
-- Perform functions necessary to provide support while preventing and troubleshooting anomalous conditions
-- Take over others’ work as needed
An organized control system for developing and maintaining situation awareness, supporting operator control, and facilitating fast decision-making surrounding automatic setup and maintenance of Deep Space Network support activities.
Research questions
Does *intervention* lead to better decisions than *control*?
Does *intervention* lead to **better decisions** than *control*?

**Increased performance**
Shorter time to task and lower error rate
*Outcome variable 1*

**Decreased perceived workload**
May be related to “display clutter”
*Outcome variable 2*

**Increased situation awareness**
As measured by subjective and objective measures
*Outcome variable 3*
Is everything okay?
Develop and maintain global situation awareness
Operationalized by postage stamp
Research Question 1

State of the future
Develop and maintain a model of the projected future
Operationalized by stamp ribbon
Research Question 2

Details and deltas
Support level-1 situation awareness with quick details; support level-2 situation awareness by calculating deltas
Operationalized by the “All” sub-display
Research Question 3

Make it visual
Use a strong data-ink ratio for large information transfer, rather than showing measurements and numbers alone
Operationalized by downlink carrier FFT display
Research Question 4

Strengthen the mental model
Arrange by spacecraft, antenna, subsystem, device, and by everything; Will filtering and search be helpful?
Operationalized by logging
Research Question 5

Making changes
Investigate appropriateness of everything-editable versus modal lock/edit states or special configuration displays
Operationalized by modals and config displays
Research Question 6

By my own rules
Investigate level-3 situation awareness with operator control for forming rulesets for realtime data processing
Operationalized by Complex Event Processing
Research Question 7
RQ1: Is everything okay?
Develop and maintain global situation awareness
RQ1: Is everything okay?
Develop and maintain global situation awareness
RQ2: State of the future

Develop and maintain a model of the projected future
### RQ3: Details and deltas

Support level-1 (perception) situation awareness with quick details; support level-2 (comprehension) situation awareness by calculating deltas

<table>
<thead>
<tr>
<th>Variable</th>
<th>Predicted</th>
<th>Measured</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>0.000 002 Hz/s/s</td>
<td>-0.072 689 Hz/s</td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>-115.599 998 Hz/s/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>-115.599 996 Hz/s/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt</td>
<td>-115.599 998 dBm</td>
<td>-477.458 405 dBm</td>
<td>361.858 407 dBm</td>
</tr>
<tr>
<td>Predicted</td>
<td>-115.599 998 dBm</td>
<td></td>
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<tr>
<td>Measured</td>
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</tr>
<tr>
<td>Delta</td>
<td>361.858 407 dBm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pc</td>
<td>-120.671 280 dBm</td>
<td>-482.229 614 dBm</td>
<td>361.558 334 dBm</td>
</tr>
<tr>
<td>Predicted</td>
<td>-120.671 280 dBm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>-482.229 614 dBm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>361.558 334 dBm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pc/No</td>
<td>-120.671 280 dB-Hz</td>
<td>482.229 614 dB-Hz</td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>-120.671 280 dB-Hz</td>
<td></td>
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<tr>
<td>Measured</td>
<td>482.229 614 dB-Hz</td>
<td></td>
<td></td>
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<tr>
<td>Delta</td>
<td>361.558 334 dB-Hz</td>
<td></td>
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<tr>
<td>Best measured</td>
<td>-300.000 000 dB-Hz</td>
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<tr>
<td>Residual</td>
<td>-362.488 037 dB-Hz</td>
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<tr>
<td>Cumulative</td>
<td>-300.000 000 dB-Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt/No</td>
<td>67.559 319 dB-Hz</td>
<td>-295.228 790 dB-Hz</td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>67.559 319 dB-Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>-295.228 790 dB-Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>-362.788 109 dB-Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total power AGC</td>
<td>1.967 773 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MP measured</td>
<td>0.000 000 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loop SP</td>
<td>-135.300 781 deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
RQ4: Make it visual

Use a strong data-ink ratio for large information transfer, rather than showing measurements and numbers alone.
RQ5: Strengthen the mental model
Arrange by spacecraft, antenna, subsystem, device, and by everything; Will filtering and search be helpful?

| 07/3505 | 10:05 | PA | ant-43 | stamp-VGR2 | 43 End of activity | VGR2 |
| 07/3506 | 10:05 | PA | ant-43 | stamp-VGR2 | 43 End of activity | VGR2 |
| 07/3507 | 7:10  | AD | ant-14 | stamp-VGR1 | 14 Beginning of activity | VGR1 |
| 07/3508 | 7:10  | AD | ant-14 | stamp-VGR1 | 14 Begin precal | VGR1 |
| 07/3509 | 7:20  | PA | ant-14 | stamp-VGR1 | 14 Antenna slewing | VGR1 |
| 07/3510 | 7:45  | DR | ant-14 | stamp-VGR1 | 14 Antenna on point | VGR1 |
| 07/3511 | 7:55  | DR | ant-14 | stamp-VGR1 | 14 Beginning of track | VGR1 |
| 07/3512 | 7:55  | DR | ant-14 | stamp-VGR1 | 14 Acquire downlink on DC11 | VGR1 |
| 07/3513 | 8:05  | DR | ant-14 | stamp-VGR1 | 14 Acquire uplink with 18KW | VGR1 |
| 07/3514 | 9:00  | DR | ant-14 | stamp-VGR1 | 14 DROP downlink LOCK | VGR1 |
| 07/3515 | 9:03  | DR | ant-14 | stamp-VGR1 | 14 Acquire downlink on DC11 | VGR1 |
| 07/3516 | 9:07  | DR | ant-14 | stamp-VGR1 | 14 One-way downlink LOCK | VGR1 |
| 07/3517 | 12:05 | DR | ant-14 | stamp-VGR1 | 14 End of track | VGR1 |
| 07/3518 | 12:05 | DR | ant-14 | stamp-VGR1 | 14 Begin postcal | VGR1 |
| 07/3519 | 12:05 | PA | ant-14 | stamp-VGR1 | 14 Antenna stowing | VGR1 |
| 07/3520 | 12:10 | PA | ant-14 | stamp-VGR1 | 14 Antenna stowed | VGR1 |
| 07/3521 | 12:15 | PA | ant-14 | stamp-VGR1 | 14 End postcal | VGR1 |
| 07/3522 | 12:15 | PA | ant-14 | stamp-VGR1 | 14 End of activity | VGR1 |
| 07/3523 | 9:45  | PA | ant-24 | stamp-MOM  | 24 Beginning of activity | MOM |
| 07/3524 | 9:45  | PA | ant-24 | stamp-MOM  | 24 Begin precal | MOM |
| 07/3525 | 9:50  | DA | ant-24 | stamp-MOM  | 24 Antenna slewing | MOM |
RQ6: Making changes
Investigate appropriateness of everything-editable versus modal lock/edit states or special
RQ7: By my own rules
Investigate level-3 (projection) situation awareness with operator control for forming rulesets for realtime data processing
Fin
Development and test plan
<table>
<thead>
<tr>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postage stamp</td>
<td>STL4 display variants LF</td>
<td>Major displays (5)</td>
<td>CEP</td>
<td>Consolidated dress rehearsal</td>
<td>Final user study</td>
</tr>
<tr>
<td></td>
<td>postase stamp ribbon</td>
<td>STL4 iteration</td>
<td>Major displays iteration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Major displays LF</td>
<td>postage stamp ribbon iteration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CEP LF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**WHAT WE TEST**

<table>
<thead>
<tr>
<th>Postage stamp #F</th>
<th>CEP input &amp; output</th>
<th>CEP input &amp; output implementation</th>
<th>Changes &amp; fixes</th>
<th>Changes &amp; fixes - no design changes</th>
<th>Results &amp; analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>STL4 and multiples</td>
<td>Major displays (5) implementation</td>
<td>CEP continued</td>
<td></td>
<td>CEP input &amp; output design</td>
<td>Final user study protocol finalize</td>
</tr>
<tr>
<td>STL4 LF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>postage stamp ribbon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major displays designed</td>
<td></td>
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</table>