The NOνA Module Factory Quality Assurance System

Alex Smith

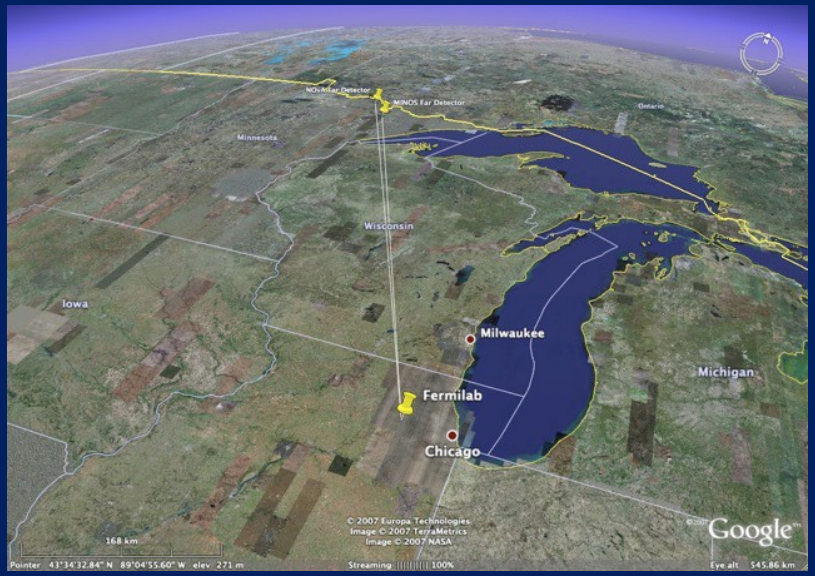
University of Minnesota

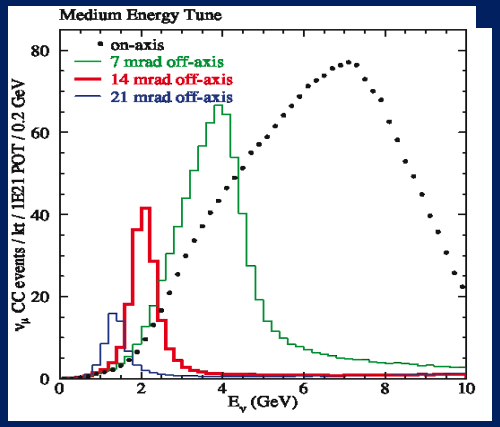
for the

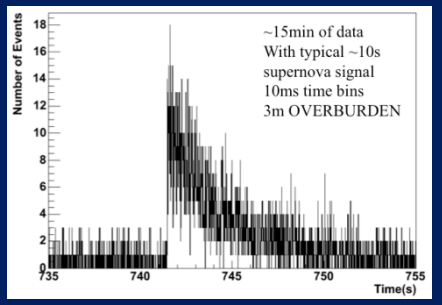
NOνA Collaboration

NOνA Physics Goals

- $\sin^2(2\theta_{13})$
- Determine neutrino mass hierarchy using MSW matter effects
  - Possible because NuMI can provide both neutrino and antineutrino beams
- Limit parameter space of δ_{CP}
- Precise measurement of $\sin^2(2\theta_{23})$
- Potential to observe neutrino flux from galactic supernovae

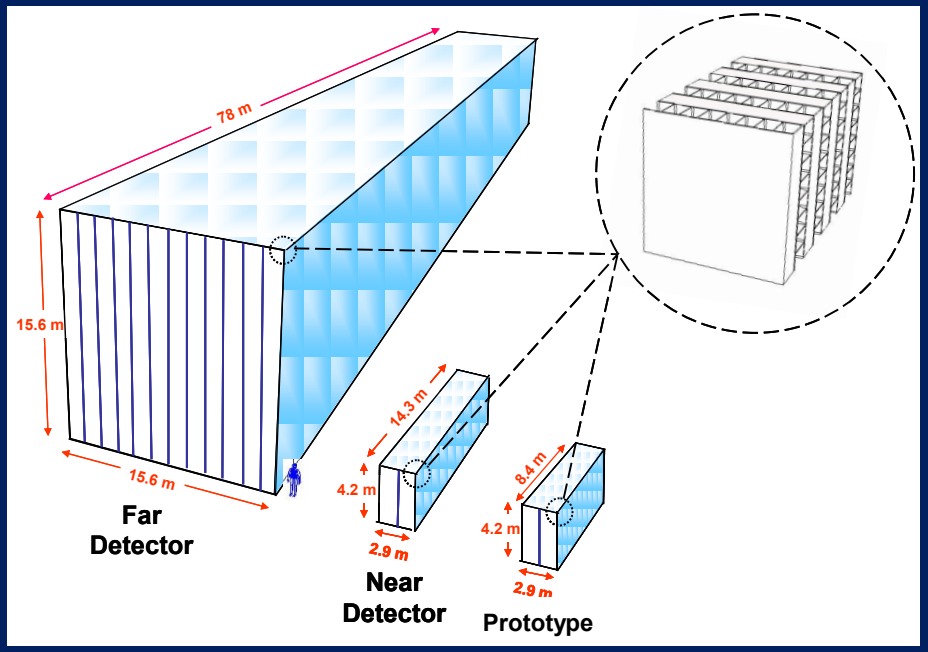


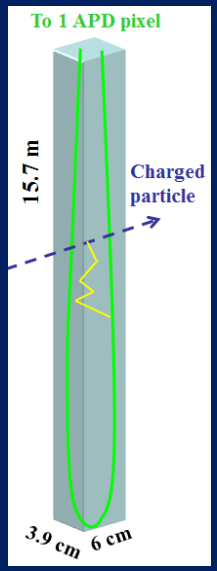


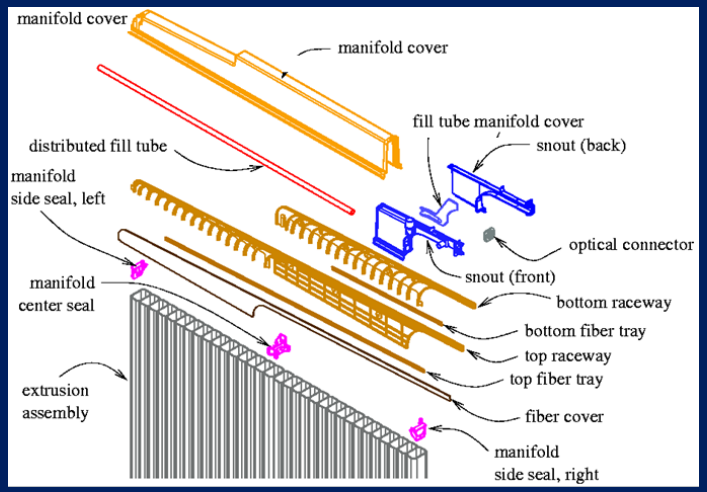


NOνA Detector Module Design

- Wavelength shifting fiber looped through tube filled with liquid scintillator
- Many custom injection-molded PVC parts required to route 64 fiber ends and seal each module
- Two adhesive seals
  - "Inner": a buffer that does not react with scintillator, but moderate strength
  - "Outer": about as strong as PVC itself
- Modules assembled 12 across and 12 high at FD site







A Matter of Scale and Cost…

- Industry-scale production operation:
  - ~12,000 modules
  - ~500 outgoing semi-truck loads of modules
  - Up to ~150 truck loads stored in factory
  - 125,000 sf production space

- Cost per module is critical
  - Student labor
  - Low reject rate: <2%
    - ~$5000 for each rejected module
- Many part-time employees
  - Up to 200-250 student employees at a time (up to 70 *in the factory* at a time)
  - 400-500 total employees for ~2.5 year duration of production

Assembly Challenges

- Build ~12000 far detector modules
- Large *part-time* University of Minnesota student work force
  - ~70 part-time employees in factory at a time during peak
  - Small full-time crew of two senior managers and five full-time managers
- Material handling
  - Modules are 16 m x 1.3 m x 0.7 m and weigh about 450 kg (1000 lbs)
  - Production of a single module spread over 5 days
  - Work on up to 150 modules at a time
  - Delay in any assembly step quickly leads to traffic jam
- Stringent technical requirements:
  - Liquid leak rate (tested with air)
    - Test: detect air leak of ~3.3 std. cc/min from a ~1,000,000 cc volume
    - 12 hour minimum test duration to reach this sensitivity
  - Flatness requirement of 0.5 mm over more than 20 m^2
  - Wavelength shifting fiber light transmission
    - Fibers easily damaged
    - Three different tests to check for damage
- **Real-time tracking of assembly process is essential**

Goals of Quality Assurance Software

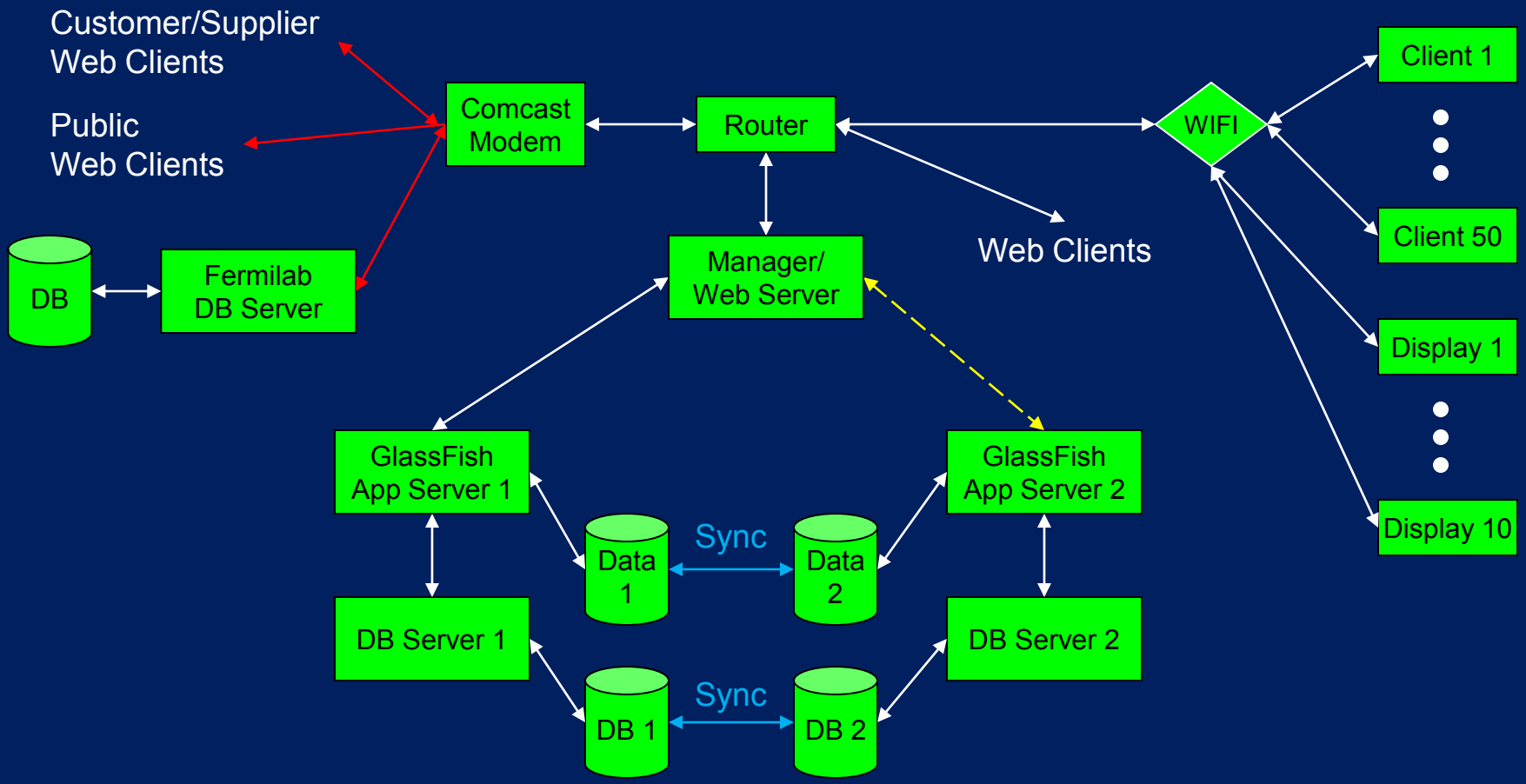
- Ensure that modules meet specifications before shipping
- Collect data during the assembly process to allow us to quickly identify, diagnose, and fix any problems that may arise.
- Interface with test devices to collect data
  - Interpret, summarize, and archive data
  - Centralize calibration data
- Guide assembly process to prevent mistakes
- Provide tools to:
  - Manage large number of part-time employees with a small team of full-time employees
  - Manage training of employees
  - Ensure quality and manage inventory of parts and materials
  - Guarantee maintenance and proper functioning of the large number of machines
  - Ensure compliance with safety standards
  - Ease reporting to safety agencies
  - Simplify reporting to project management

Software Framework

- Built on Java Enterprise Edition (Java EE)
  - Multi-tiered enterprise application
- Deployed on GlassFish application server cluster
  - Two servers
  - Failover
- PostgreSQL database
  - Two servers
  - Sync to hot failover
- Web tier
  - Based on Servlets, PHP, and JSF

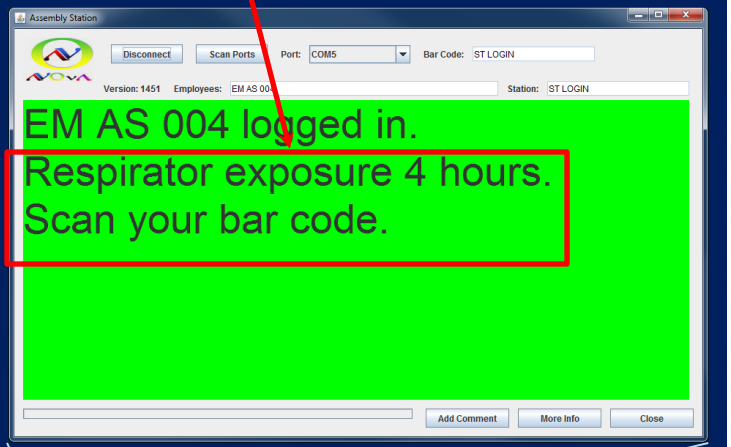
- Client tier
  - Java GUI application clients
  - Started from Java WebStart
    - Downloads/installs code if needed
    - Auto update of code if changed
  - Provide interface to employees
    - Instructions
    - Error alerts
    - Audio and voice feedback
  - Receive input primarily from Bluetooth bar code scanners and touchscreen panels

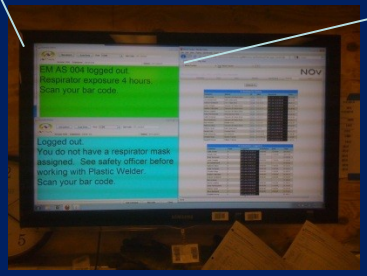
Hardware Architecture



Employee Management

- Login/logout to track actual hours
- Online scheduler
  - Students schedule themselves
- Employees scan into their tasks
- Safety equipment tracking





1 Not Working On Task

ID	Employee	Worker	Team	Logged In	No Task	Time
8182	[redacted]	student	6	2011-04-15 13:20:04	00:28:18	03:25:25

21 Working On Factory

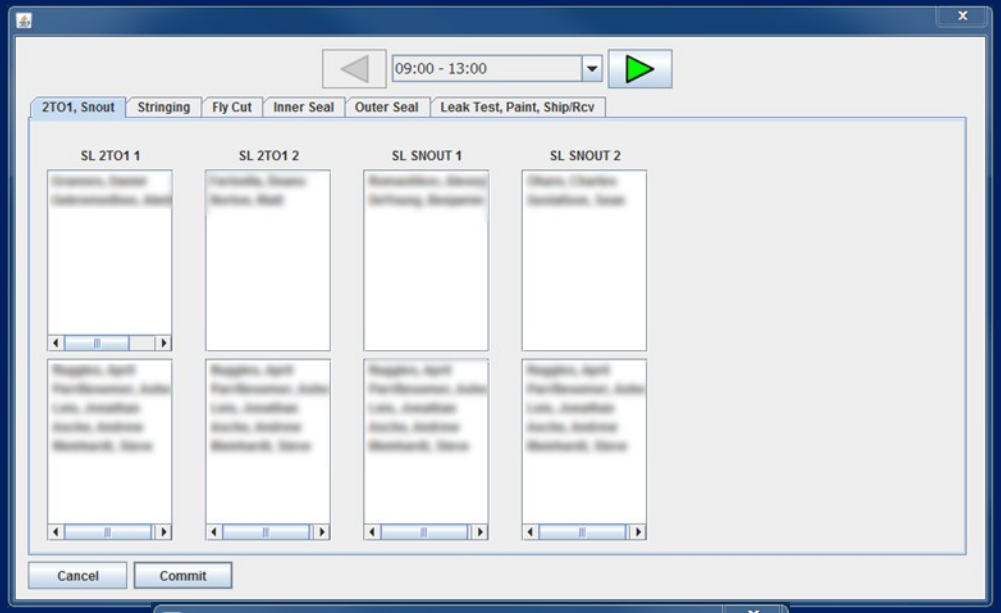
Employee	Station	ID	WBS	Started At	Time
[redacted]	2 to 1 Table Work	35732	2.5.3.1.5	2011-04-15 16:26:06	00:19:24
[redacted]	Fiber Tester Work	35731	2.5.3.1.8	2011-04-15 16:24:48	00:20:42
[redacted]	Crossbot Work	35729	2.5.3.1.13	2011-04-15 16:10:54	00:34:35
[redacted]	String Machine Puller Work	35727	2.5.3.1.7	2011-04-15 16:00:20	00:45:10
[redacted]	Bubbler work	35725	2.5.3.1.4	2011-04-15 14:57:39	01:47:51
[redacted]	Cleaning Factory	35723	2.5.3.2.5	2011-04-15 14:47:26	01:58:04
[redacted]	Cleaning Factory	35722	2.5.3.2.5	2011-04-15 14:47:26	01:58:04
[redacted]	Crossbot Work	35721	2.5.3.1.13	2011-04-15 14:42:34	02:02:55
[redacted]	2 to 1 Table Work	35720	2.5.3.1.5	2011-04-15 14:27:54	02:17:35
[redacted]	QA Software	35719	2.5.3.2.6.8	2011-04-15 14:26:21	02:19:08
[redacted]	2 to 1 Table Work	35717	2.5.3.1.5	2011-04-15 14:18:35	02:26:55
[redacted]	2 to 1 Table Work	35716	2.5.3.1.5	2011-04-15 13:56:29	02:49:01
[redacted]	QA Software	35713	2.5.3.2.6.8	2011-04-15 13:51:09	02:54:21
[redacted]	Bubbler work	35711	2.5.3.1.4	2011-04-15 13:28:12	03:17:18
[redacted]	Module Research	35709	2.5.1.1.11	2011-04-15 13:23:03	03:22:27
[redacted]	Bubbler work	35708	2.5.3.1.4	2011-04-15 13:22:53	03:22:37
[redacted]	String Machine Puller Work	35706	2.5.3.1.7	2011-04-15 13:12:59	03:32:31
[redacted]	Fulltimer Training	35703	2.5.3.2.6.15	2011-04-15 13:09:15	03:36:14
[redacted]	Vacuum Lift Fixture Work	35694	2.5.3.1.1	2011-04-15 12:46:03	03:59:27
[redacted]	Vacuum Lift Fixture Work	35691	2.5.3.1.1	2011-04-15 12:34:28	04:11:02
[redacted]	Module Research	35673	2.5.1.1.11	2011-04-15 09:31:32	07:13:58

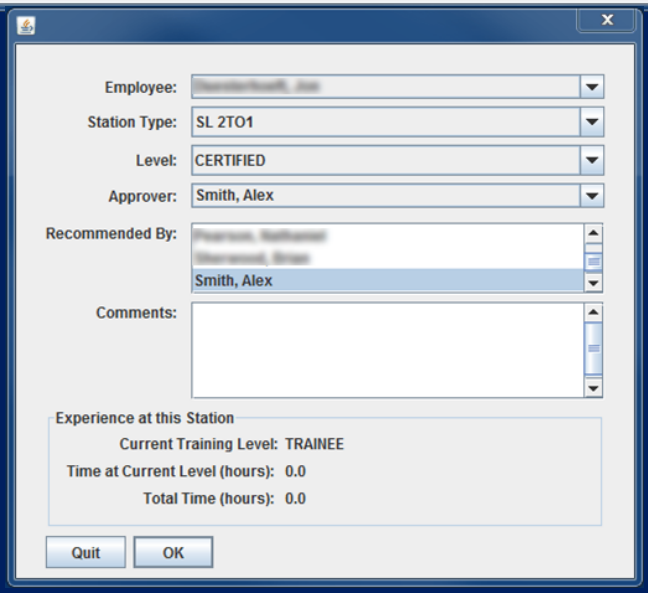
23 Scheduled / Logged In

Employee	Team	Logged In	Scheduled	Until	Logout	Time
[redacted]	6	No	13:00:00	17:00:00	-	00:00:00
[redacted]	5	2011-04-15 14:57:35	14:00:00	17:00:00	Logout	01:47:55
[redacted]	2	2011-04-15 14:36:26	No	-	Logout	02:09:04

Labor Allocation and Training

- Managers use “Day Planner” tool to decide how to allocate the day’s work force
- Employee training is indicated for each assembly process group
  - Training defined for each group of assembly procedures
- We plan to add algorithms to choose starting labor allocation based on selected priorities





Reporting and Compliance

- Many workers and machines to keep track of
- Safety Compliance
  - Data to demonstrate compliance with safety standards is collected
    - Respirator usage and maintenance
    - Gantries and lifting device maintenance
- Expenditure reporting to project management
  - Employees track their work by scanning corresponding bar codes

Total Hours: 3462.57

Work Hours Distribution (1 - 46 of 46)

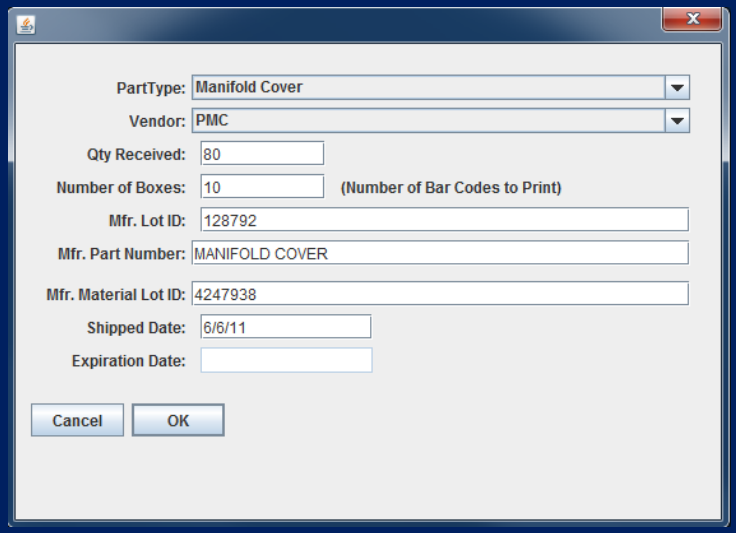
From 2011-03-15 : To 2011-04-15 : Group By WBS Update

WBS	First	Last	Hours	Bar Graph	Percent	Worker All	Type All
2.5.3.1.1	2011-03-15	2011-04-15	552.38		15.953	student	factory
2.5.3.1.5	2011-03-15	2011-04-15	421.21		12.165	student	factory
2.5.3.1.4	2011-03-15	2011-04-15	263.19		7.601	fulltime	factory
2.5.3.1.4	2011-03-15	2011-04-15	255.61		7.382	student	factory
2.5.3.2.6.15	2011-03-15	2011-04-15	235.51		6.802	student	factory
2.5.3.2.5	2011-03-15	2011-04-15	216.85		6.263	student	factory
2.5.3.2.6.8	2011-03-15	2011-04-15	174.6		5.042	student	factory
2.5.3.1.7	2011-03-15	2011-04-15	167.41		4.835	student	factory
2.5.3.1.3	2011-03-16	2011-04-15	138.45		3.998	student	factory
2.5.3.2.6.15	2011-03-15	2011-04-15	134.93		3.897	fulltime	factory
2.5.3.1.8	2011-03-17	2011-04-15	132.23		3.819	student	factory
2.4.5.3	2011-03-15	2011-04-15	129.36		3.736	student	factory
2.5.3.2.6.8	2011-03-15	2011-04-15	95.6		2.761	fulltime	factory
2.5.3.3	2011-03-25	2011-04-14	85.79		2.478	student	module
2.5.3.1.13	2011-03-16	2011-04-15	77.9		2.25	student	factory
2.5.3.1.1	2011-03-21	2011-04-06	76.42		2.207	fulltime	factory
2.5.1.1.11	2011-03-15	2011-04-15	58.74		1.696	student	factory
2.5.3.1.13	2011-03-15	2011-04-15	48.86		1.411	fulltime	factory
2.5.3.2.6.8	2011-03-16	2011-04-15	32.6		0.941	postdoc	factory
2.5.3.1.5	2011-03-15	2011-04-15	30.76		0.888	fulltime	factory
2.5.1.1.11	2011-03-29	2011-04-05	29.84		0.862	postdoc	factory
2.5.3.3	2011-03-15	2011-04-14	29.35		0.848	fulltime	module
2.5.3.1.10	2011-03-16	2011-04-13	28.32		0.818	fulltime	factory
2.5.3.3	2011-03-28	2011-04-13	14.01		0.405	student	factory

- Payroll
  - Required data is collected to automate payroll
  - We plan to switch to automated timesheet generation soon

Inventory Management

- Shortage of part or supply could have serious impact on project schedule
- Some injection molded parts have lead times on the order of months
- Adhesives have limited shelf life
  - Cannot be ordered too far in advance
  - Shelf life must be checked before use
- Many small items to track
  - Adhesive mixing nozzles
  - Bar code labels
- Alarm system alerts management when inventory drops below configurable warning and error thresholds
- Tools for receiving and checking out parts

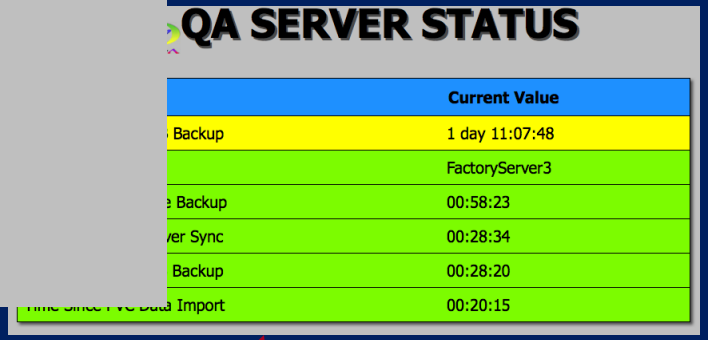


Partlot (1 - 45 of 45)

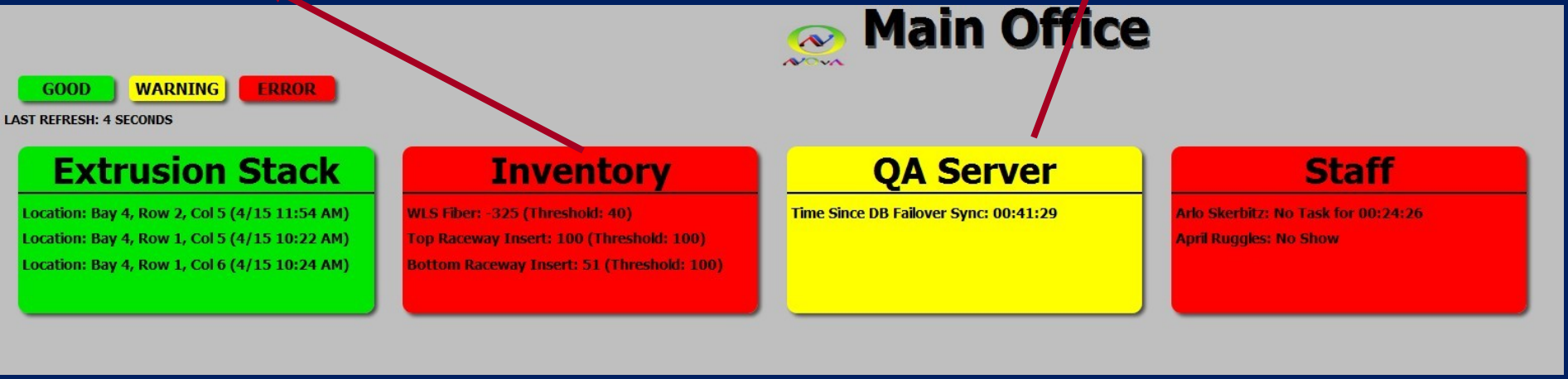
ID	Part Type	Vendor	Mfr Lot ID	Mfr Part #	Shipped	Inserted	Invt	Rcvd
	All				:	:		
PT EXTCS 1	EXTCS	ASTRO	JIM/1/05/03/11	5671WHT1.968	2011-05-03	2011-05-05	25000	25000
PT FRR 2	FRR	PIONEER	14221	1394	2010-09-02	2010-09-03	7038	9600
PT MCS_H 2	MCS_H	PIONEER	14220	361-ASM	2010-09-13	2010-09-13	700	700
PT MCS_V 1	MCS_V	PIONEER	ND Version 1	-	2010-08-27	2010-08-27	662	-
PT ES 2	ES	ASTRO	CRAIG/2/3/16/11	4981WHT52.165	2011-03-18	2011-03-21	510	510
PT OC 2	OC	OLSEN	1619	OPTCONN7 Rev. A	2010-09-15	2010-09-15	343	345

Alarm Systems and Displays

- Can be configured with relevant information for each factory location



Part Name	Inventory	Warning	Threshold
Top Raceway Insert	100	200	100
Bottom Raceway Insert	51	200	100
WLS Fiber	-325	100	40
Fiber Retaining Ring	7038	6400	3200
Optical Connector	368	200	100
Bottom Raceway	260	200	100



Configurable Alarm Displays

Location of stacks

Extrusion ID	Bay	Row	Column	Out of Tolerance	Damaged	Missing Data
XTRVXTA0000617	3	3	3	YES	NO	NO
XTRVXTA0000618	3	3	3	YES	NO	NO
XTRVXTA0000613	3	3	3	YES	NO	NO
XTRVXTA0000619	3	3	3	YES	NO	NO
XTRVXTA0000620	3	3	3	YES	NO	NO
XTRVXTA0000608	3	3	3	YES	NO	NO
XTRVXTA0000609	3	3	3	YES	NO	NO
XTRVXTA0000621	3	3	3	YES	NO	NO
XTRVXTA0000616	3	3	3	YES	NO	NO
XTRVXTA0000612	3	3	3	YES	NO	NO
XTRVXTA0000629	3	3	3	NO	NO	NO
XTRVXTA0000561	3	3	3	NO	NO	NO

Extrusion details

```
   STATUS      EXTRUSION(ITEM#)     VALUE (   LOWER-   UPPER) DESCRIPTION
   ------      ----------------     ------ (   ------   ------) -----------
OUT OF SPEC   XTRVXTA0000617(15)     2.05 (   -2.00-    2.00) Web location stackup
```

<< View All >>

Extrusion

Field	Value
ID	XTRVXTA0000617
Out Of Tol	Yes
Missing QC	No
Damaged	No

Extrusion Comment (1 - 1 of 1)

ID	Extrusion	Inserted	Comment
125	XTRVXTA0000617	2011-03-07 16:21:11	STATUS EXTRUSION(ITEM#) VALUE (LOWER- UPPER) DESCRIPTION OUT OF SPEC XTRVXTA0000617(15) 2.05 (-2.00- 2.00) Web location stackup

Main Office

GOOD WARNING ERROR

LAST REFRESH: 4 SECONDS

Extrusion Stack
Location: Bay 4, Row 2, Col 5 (4/15 11:54 AM)
Location: Bay 4, Row 1, Col 5 (4/15 10:22 AM)
Location: Bay 4, Row 1, Col 6 (4/15 10:24 AM)

Inventory
WLS Fiber: -325 (Threshold: 40)
Top Raceway Insert: 100 (Threshold: 100)
Bottom Raceway Insert: 51 (Threshold: 100)

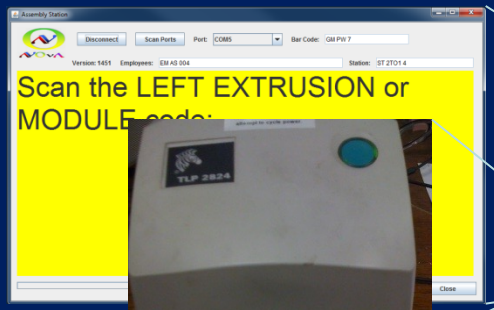
QA Server
Time Since DB Failover Sync: 00:41:29

Staff
Arlo Skerbitz: No Task for 00:24:26
April Ruggles: No Show

Assembly Tracking and Checks

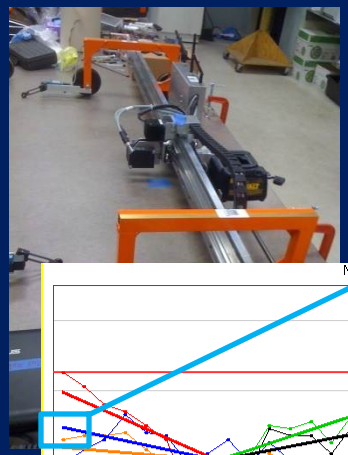
Example: Joining two extrusions:

- The scanner interface panel guides the employee through assembly process
- Scans capture ID of employees, gluing jig, adhesive dispenser, extrusion ID's, lifting fixture.
- Checks:
  - Does employee have a respirator assigned?
  - Are respirator cartridges within the exposure threshold?
  - Are extrusions within tolerance? Any missing data?
  - Are two extrusion heights compatible with each other?
  - Are module lifter, gantry, and hoist current on their scheduled service and inspection?
  - Is the adhesive dispenser current on its maintenance and ratio calibration?
- Automatically determines next module ID from database and prints bar code labels
- Starts adhesive cure timer when module is clamped and sounds bell when ready.

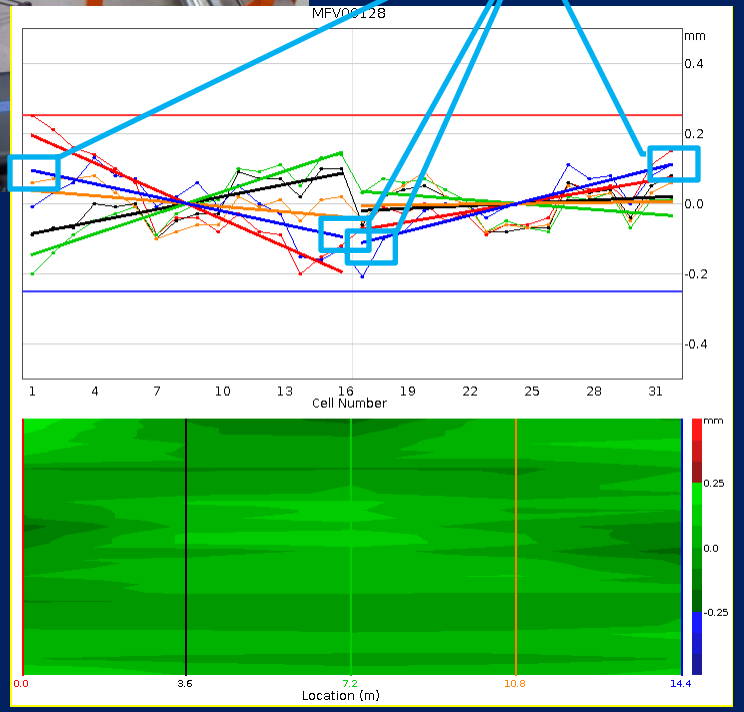


Assuring Module Flatness

- Flatness of module impacts strength of detector structure
- Custom robot drives down module to measure flatness of the module
  - Employee is alerted if module is out of tolerance
- Alarm is displayed on factory monitor panel
- Data is uploaded to the database and is viewable on the web



Ends of fit to each extrusion must fall within tolerance



Flatness measurement made for each cell at 5 locations along length of module

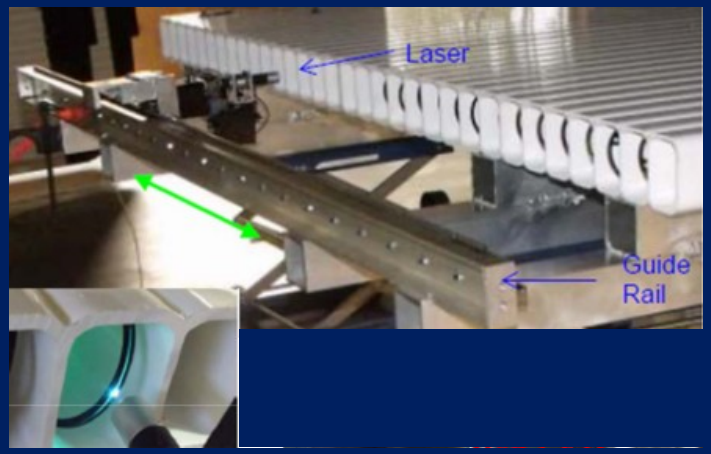
Installation of WLS Fibers

- Added extra fiber tests based on prototype detector experience
  - Throwing away a module costs >$5000
  - Test fibers as early as possible when they can be replaced
  - Test at several stages of assembly
- Fiber loops are pulled down cells using semi-automated pulling device
  - Control and feedback through touch screen panels
- Tension measured and controlled
  - Alarm if tension threshold exceeded
- Fiber transmission measured during pull
  - Alarm if insufficient or sharp drop in transmission
- Fibers threaded through guide channels and optical connector

Additional QA of WLS Fiber

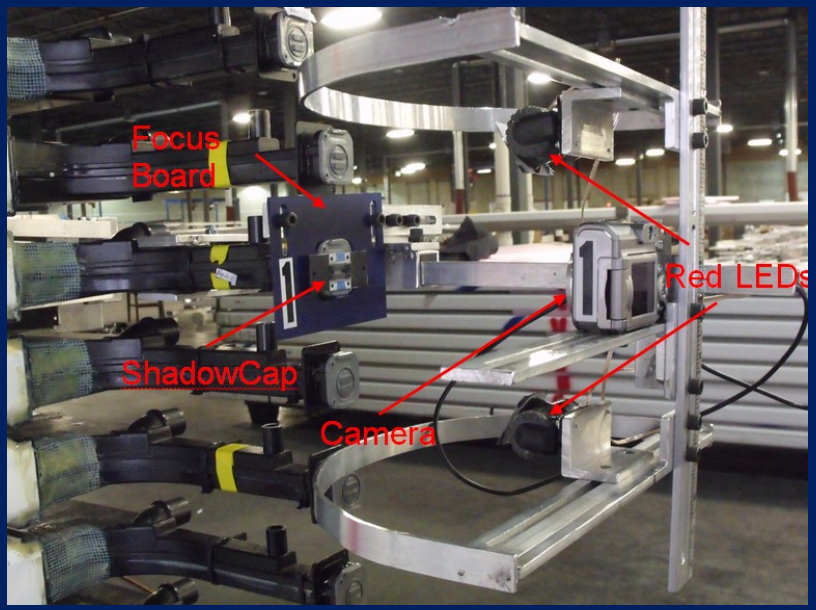
Open-End Laser Test Robot

- Shine laser on exposed far end of fiber loop
- Compare light output against expected output

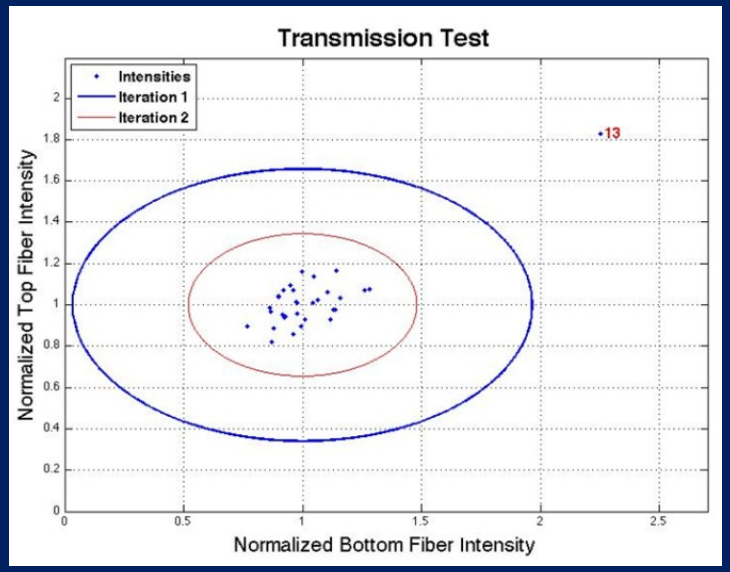


Closed End Test

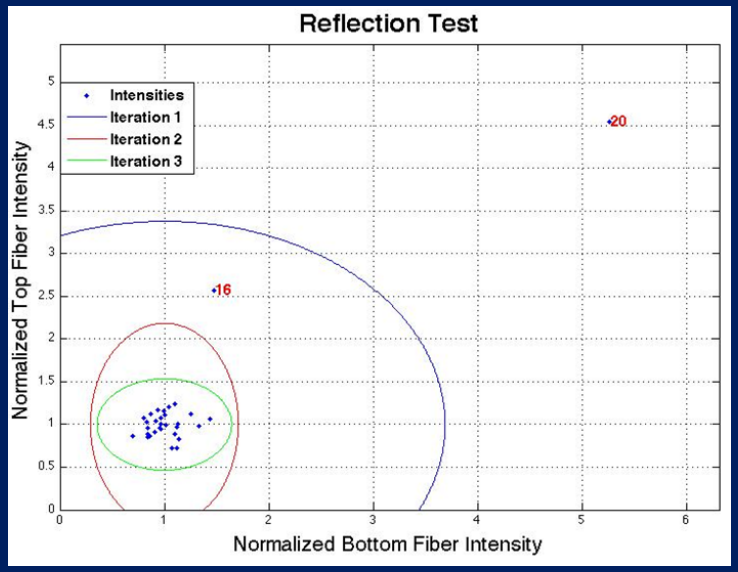
- Measure reflected and transmitted light from each end while illuminating other end
  - Use camera to measure light



Closed Module Fiber Test

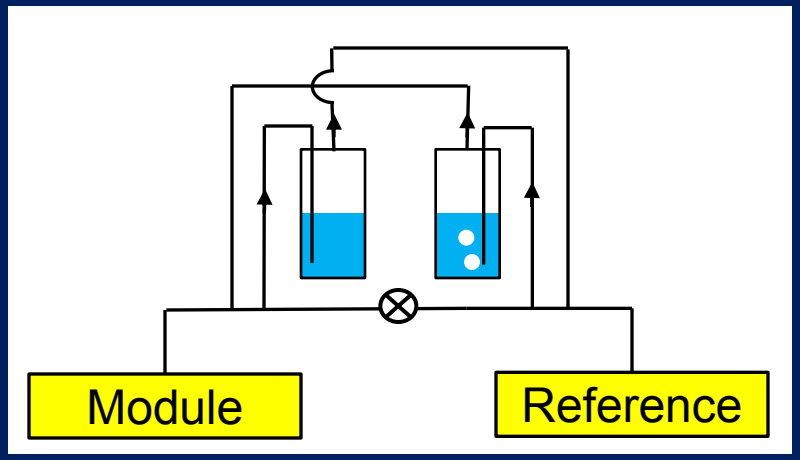


- Plot transmission intensities from each end of fiber
  - Apply 4σ cut
  - Reject outliers as bad
  - Refit and apply 4σ cut



  - Continue until no fibers are rejected
- Perform same analysis using reflected intensities

Module Leak Test



- Tester measures flow by counting bubbles passing between equalized test module and reference
- Up to 32 modules per tester
- 12 hour test duration

Conclusions

- System was used to build NOνA prototype detector
  - Added additional QA steps based on experience
- Currently being used for first steps of far detector assembly
- This system is key to meeting the challenges ahead of us
  - Build ~12000 far detector modules
  - Meet stringent tolerances
  - Manage large part-time work force with small full-time crew
- Ongoing development to address new needs and concerns as they arise