LIGO-G970164-00-M

LIGO

The LIGO Program Advisory Committee
PAC-2 Agenda
MIT
Compton Room - Building 26-110
June 12-13, 1997

Thursday - June 12, 1997

8:30 am - 9:00 am	Continental Breakfast	
9:00 am - 9:30 am	MIT Welcome	(President C. Vest)
9:30 am - 10:00 am	LIGO Status	(B. Barish or G. Sanders)
10:00 am - 12:00 pm	MIT PROGRAM PLAN	
10:00 am - 10:15 am	Overview	(R. Wiess)
10:15 am - 10:45 am	Support of Initial LIGO Installation and Operations	(M. Zucker)
10:45 am - 11:15 am	New Laboratory Facilities and Advanced Detector Research	(D. Shoemaker)
11:15 am - 11:45 am	Data Analysis	(P. Fritschel)
12:00 pm - 1:00 pm	Lunch	
1:00 pm - 1:30 pm	LIGO Laboratory and Scientific Collaboration	(B.Barish or G. Sanders)
1:30 pm - 2:00 pm	Overview of the Data Analysis System (DAS)	(A. Lazzarini)
2:00 pm - 3:00 pm	Simulation and Modeling Activities	(H. Yamamoto and L. Sievers)
3:00 pm - 3:15 pm	Break	
3:15 pm - 5:00 pm	PAC Executive Session (Closed)	
6:30 pm	Dinner at the Legal Sea Foods	

Friday - June 13, 1997

8:30 am - 9:00 am	Continental Breakfast	
9:00 am - 10:00 am	Data Analysis Environment	(B. Allen and R. Williams)
10:00 am - 10:30 am	Software and Hardware Standardization	(K. Blackburn)
10:30 am - 11:00 am	On-Line Analysis and Off-Line Analysis	(A. Lazzarini)
11:00 am - 11:30 am	Reduced Data Sets	(R. Weiss)
11:30 am - 12:00 pm	Networking Issues and Status	(A. Lazzarini)
12:00 pm - 1:00 pm	Lunch	
1:00 pm - 1:20 pm	Plans for New MIT Laboratory and Schedule for Relocation	(MIT Physical Plant Representative)
1:20 pm - 2:30 pm	Tour of Current LIGO/MIT Facilities	(R. Weiss)
2:30 pm - 4:00 pm	PAC Executive Session *(closed)*	
3:00 pm - 3:15 pm	Break	
4:00 pm - 5:00 pm	Closeout	

Agenda updated: May 21, 1997.

LIGO

Status and Plans

Barry Barish

PAC - 2

June 1997

LIGO Status

- **Construction Project**
  - » Facilities are under construction with no major technical problems
  - » Good progress on R & D, on FMI,PNI and 40m
  - » Detector design is moving forward
- LIGO Laboratory
  - » LIGO Laboratory Charter (new version)
  - » Operations (sites, data analysis, etc)
  - » Advanced R&D ($0.9M FY97)
- LIGO Scientific Collaboration (LSC)
  - » formation plan (revised)
  - » MOUs and Attachments underway
  - » Initial collaboration meeting - August 97 at LSU
- Data Analysis Systems
  - » modeling, data formats, data analysis, networking and computing (white paper)

Technical Status
facilities

- Hanford Construction
  - » foundation and slab - complete
  - » x arm beam tube, enclosure - complete
  - » y arm beam tube - underway
  - » buildings well along

- Louisiana Construction
  - » berm complete, being stabilized
  - » differential settling is OK
  - » poured first concrete; beginning construction

- Technical Status
  - » beam tube dimensions, welding, survey meet specifications.
  - » no leaks found on 65 ft sections or girth welds
  - » full 2 km x arm module pumpdown - succesful
  - » bakeout technical plan and schedule
  - » baffles - replace with uncoated baffles that meet our requirements

Technical Status
detector

- R & D Program
  - » PNI noise studies and conversion to 1.06 μ
  - » 40m conversion to recycling configuration
  - » submitted a revised advanced r&d workplan('97) and we are beginning program
- Detector
  - » Laser development at Lightwave and prestablization at Caltech
  - » Input and Core Optics
  - » Seismic Isolation (HYTEC)
  - » Length and Alignment Sensing
  - » Electronics (controls and data acquizition)

Technical Status

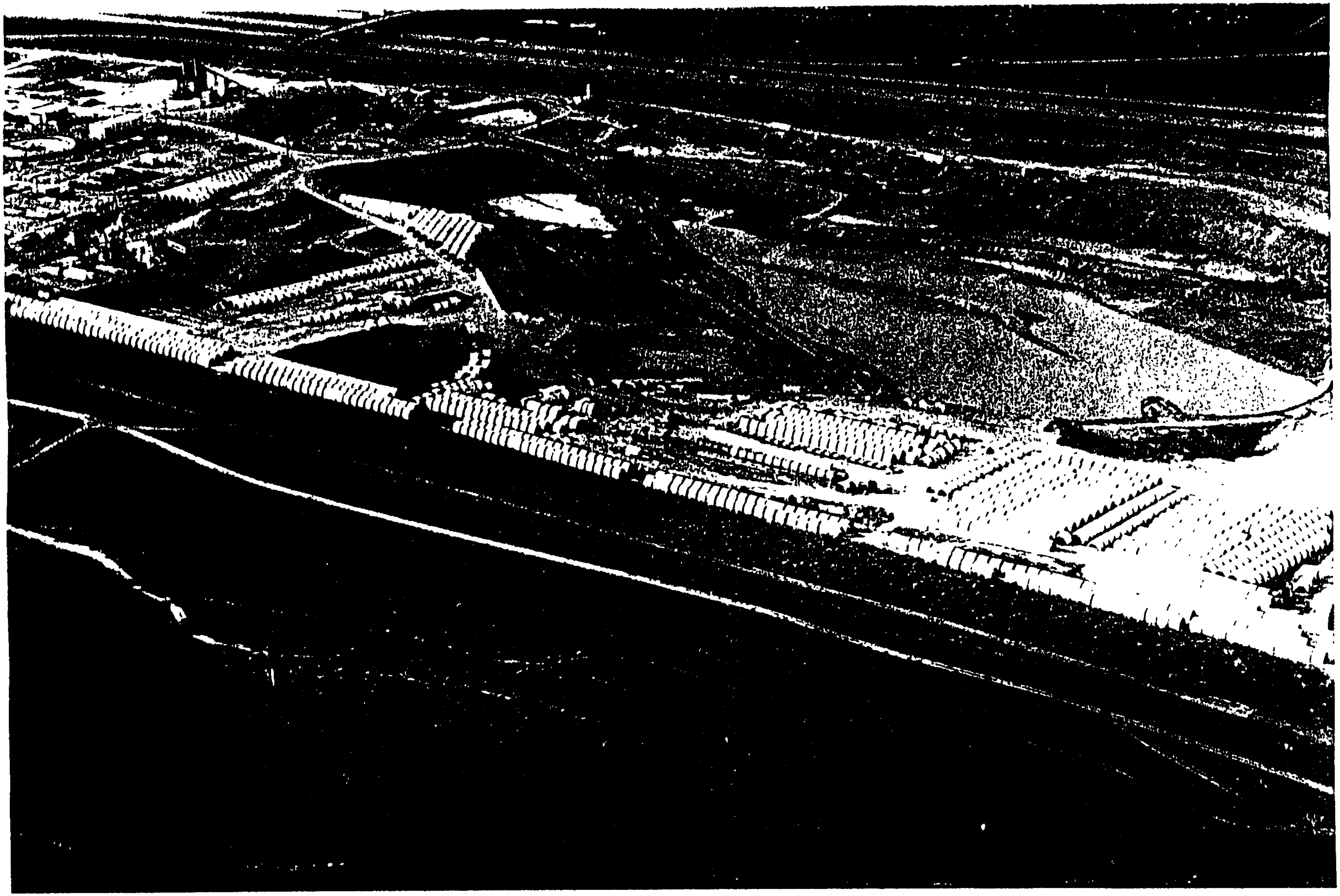
data and computing

- Data Acquisition
  - » up to 600 Gbytes/day (continuous)
- Data Processing
  - » plans, GRASP package, 40m prototype data analysis
- Networking
  - » requirements and analysis of options
- Modeling - lock acquisition
- End to End Modeling
  - » 40m validation and LIGO

White Paper for PAC - 2

PAC - 2
goals

- LIGO program and plans at MIT
  - » staffing plan
  - » R&D facilities at MIT
  - » role in commissioning detectors
  - » analysis effort at MIT
- LIGO Laboratory
  - » charter to be submitted to Caltech/MIT & NSF
- Scientific Collaboration
  - » revised formation plan
  - » first meeting at LSU in August
  - » Florida, JILA, LSU, Michigan, Penn State, Stanford, Syracuse
  - »
- Computing and Data Analysis
  - » approach; hardware; software, etc



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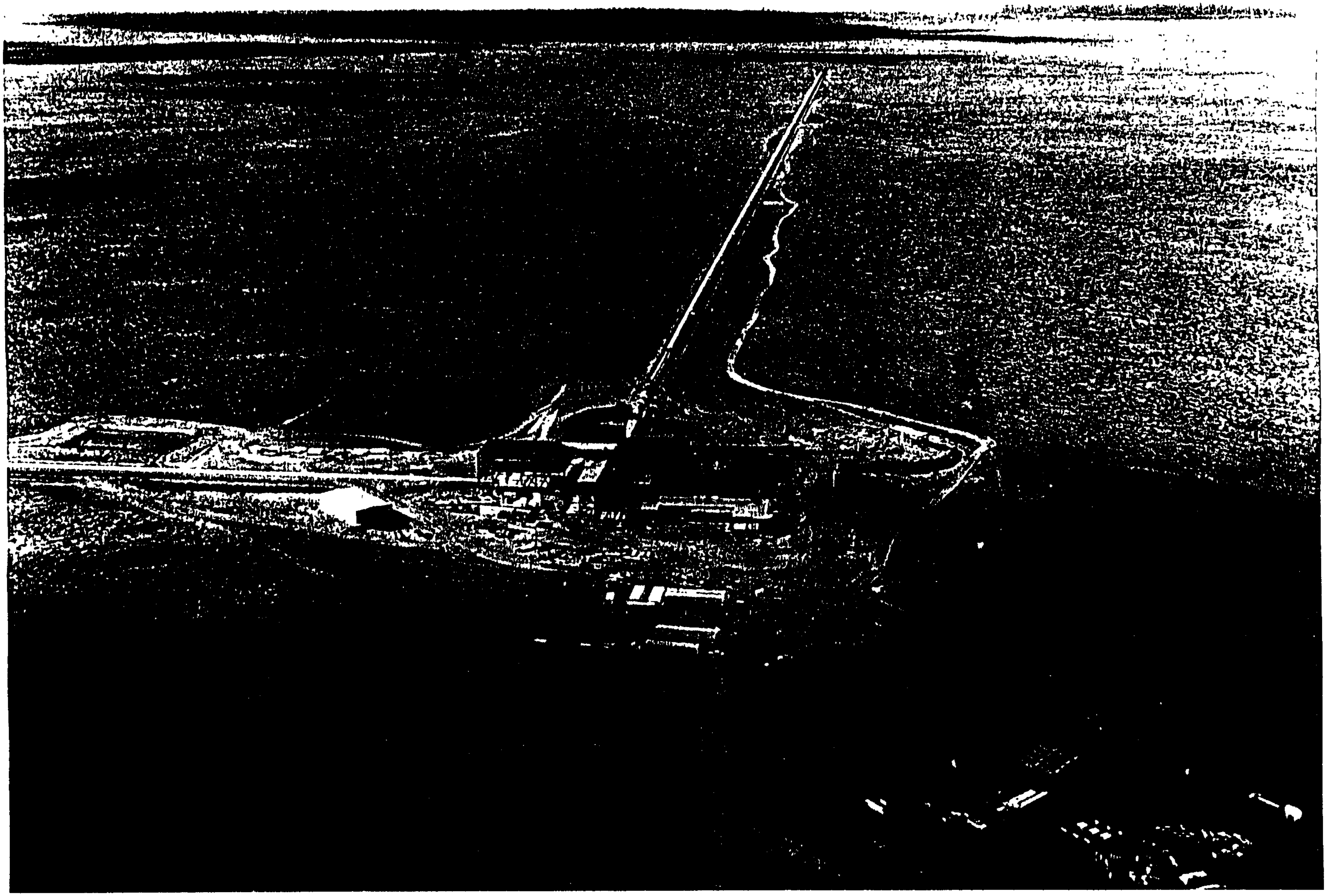

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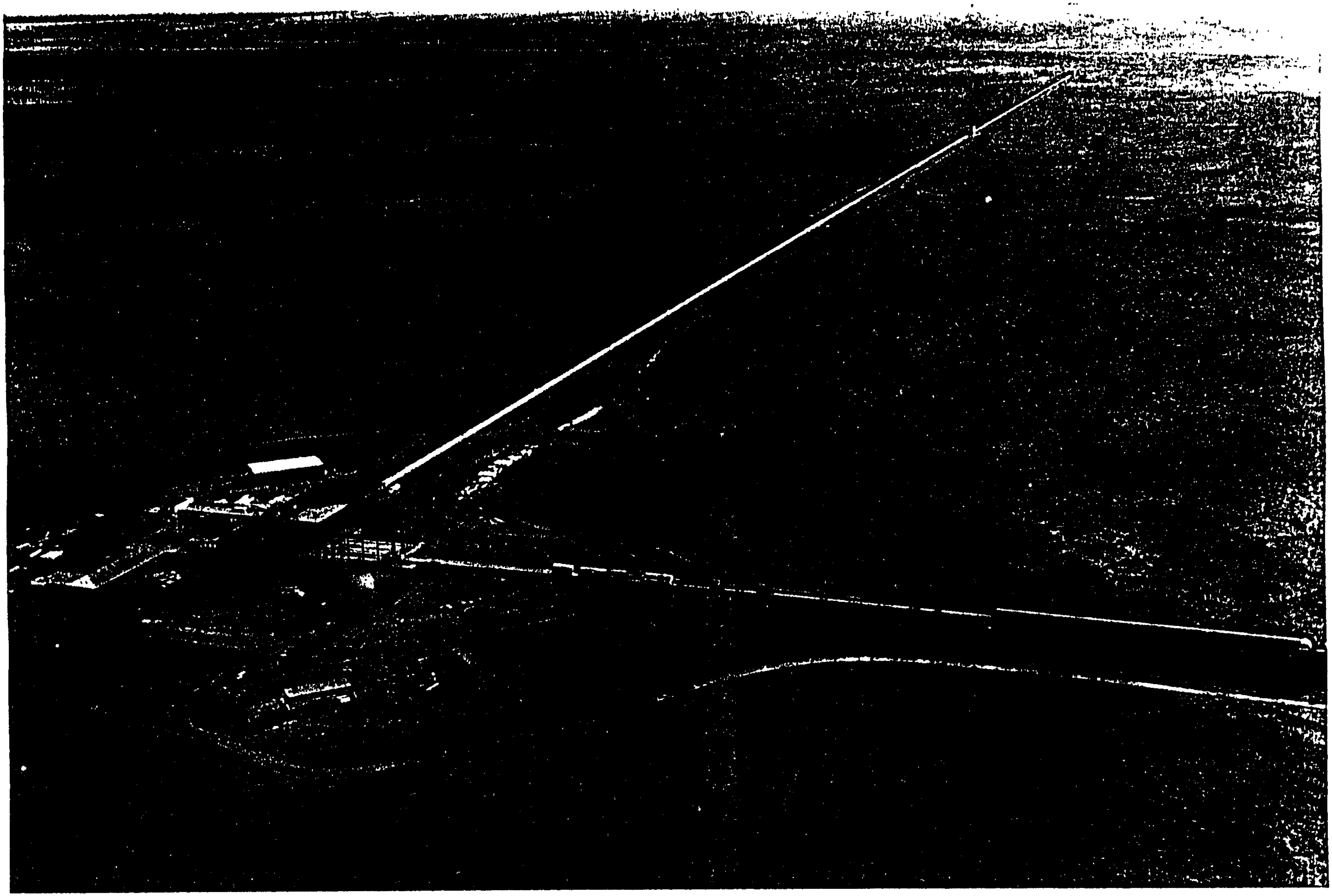

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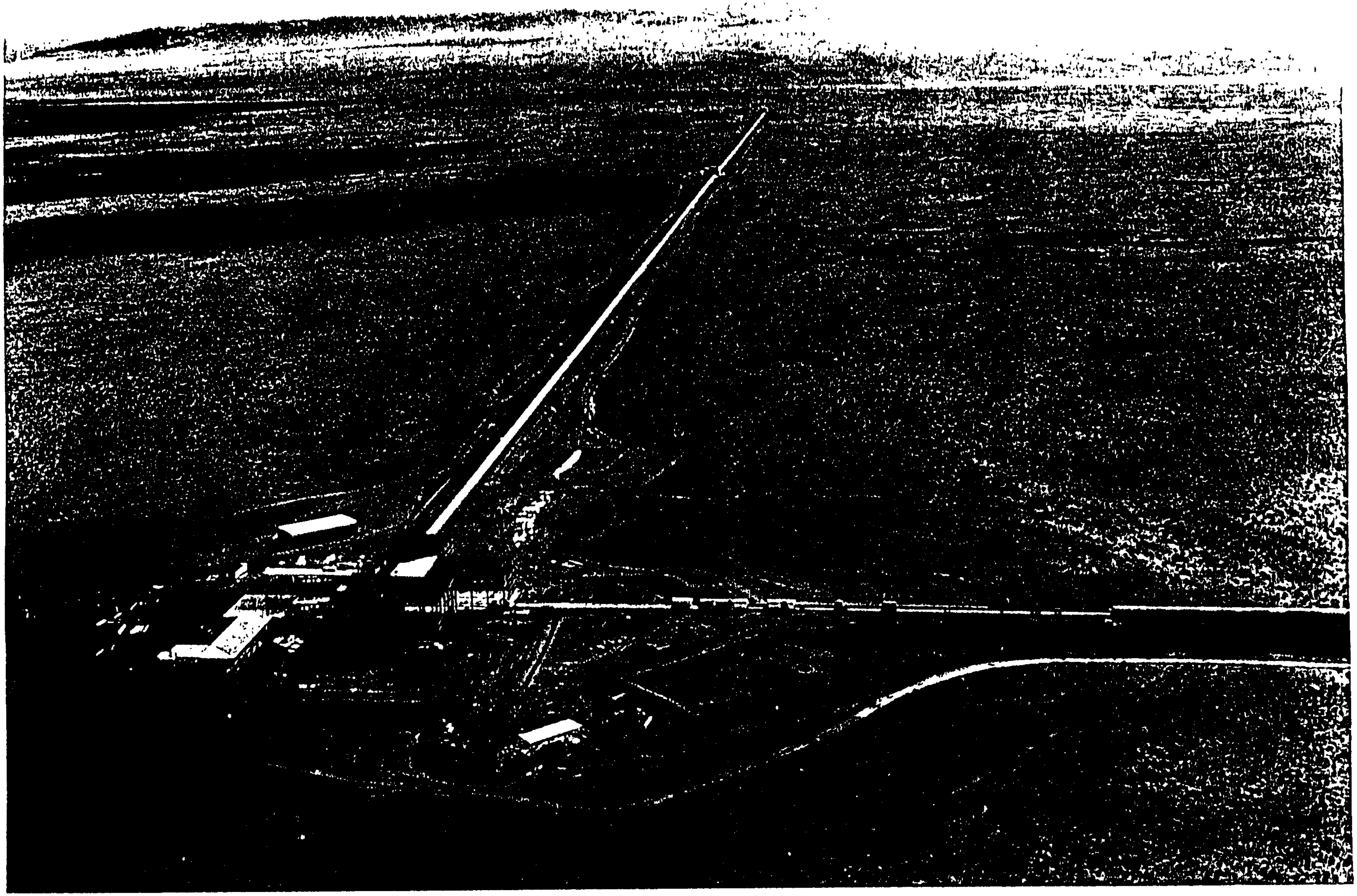

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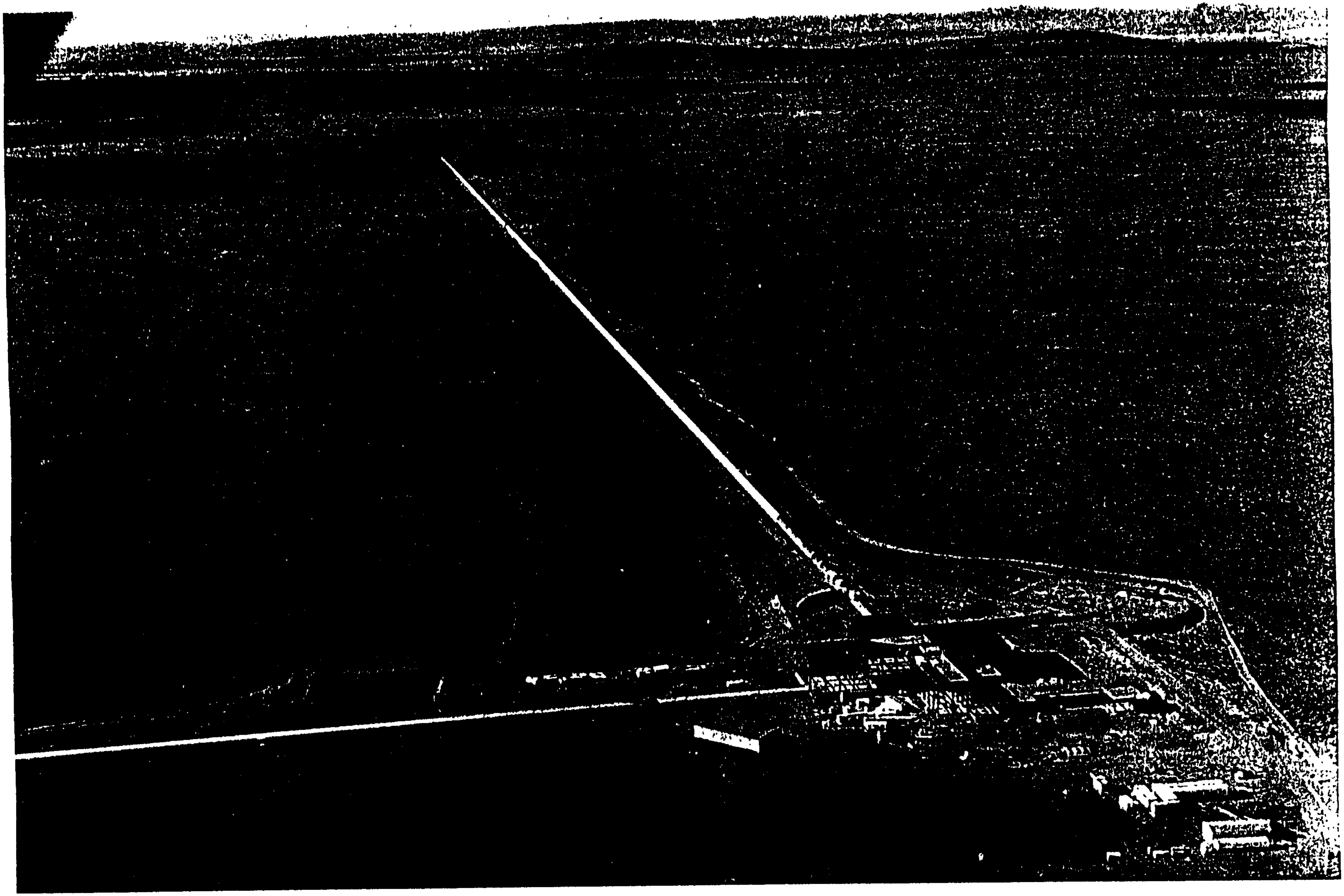

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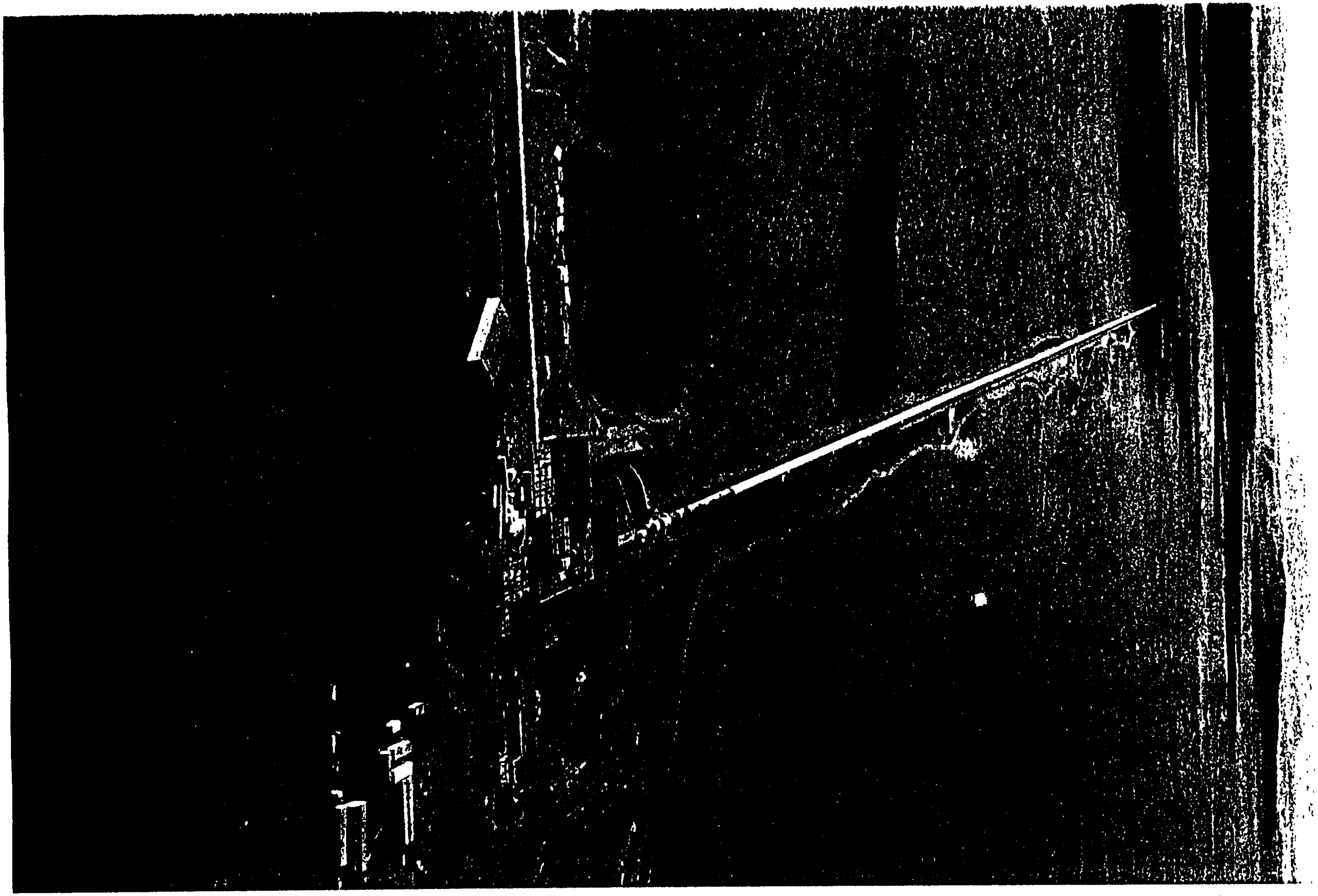

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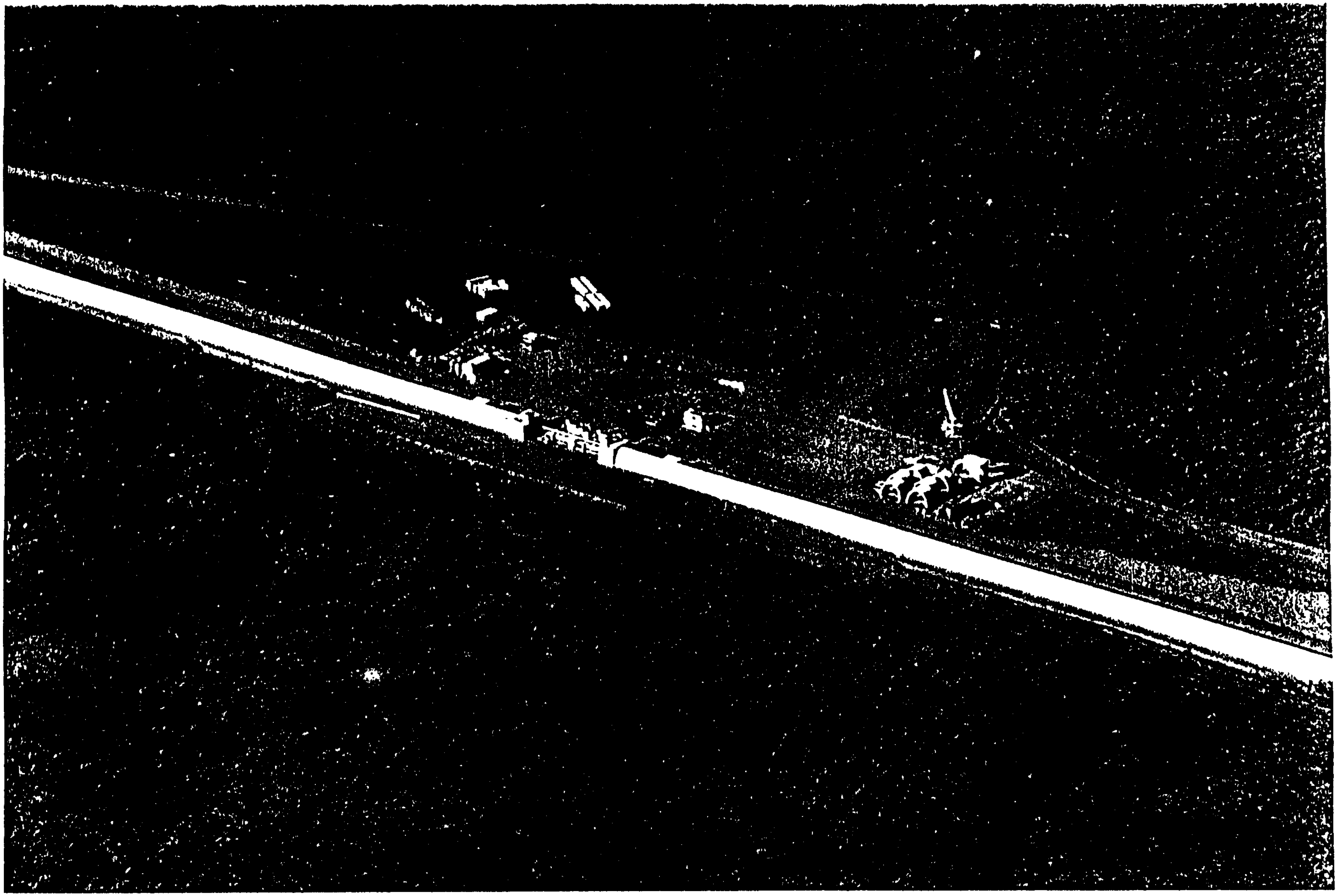

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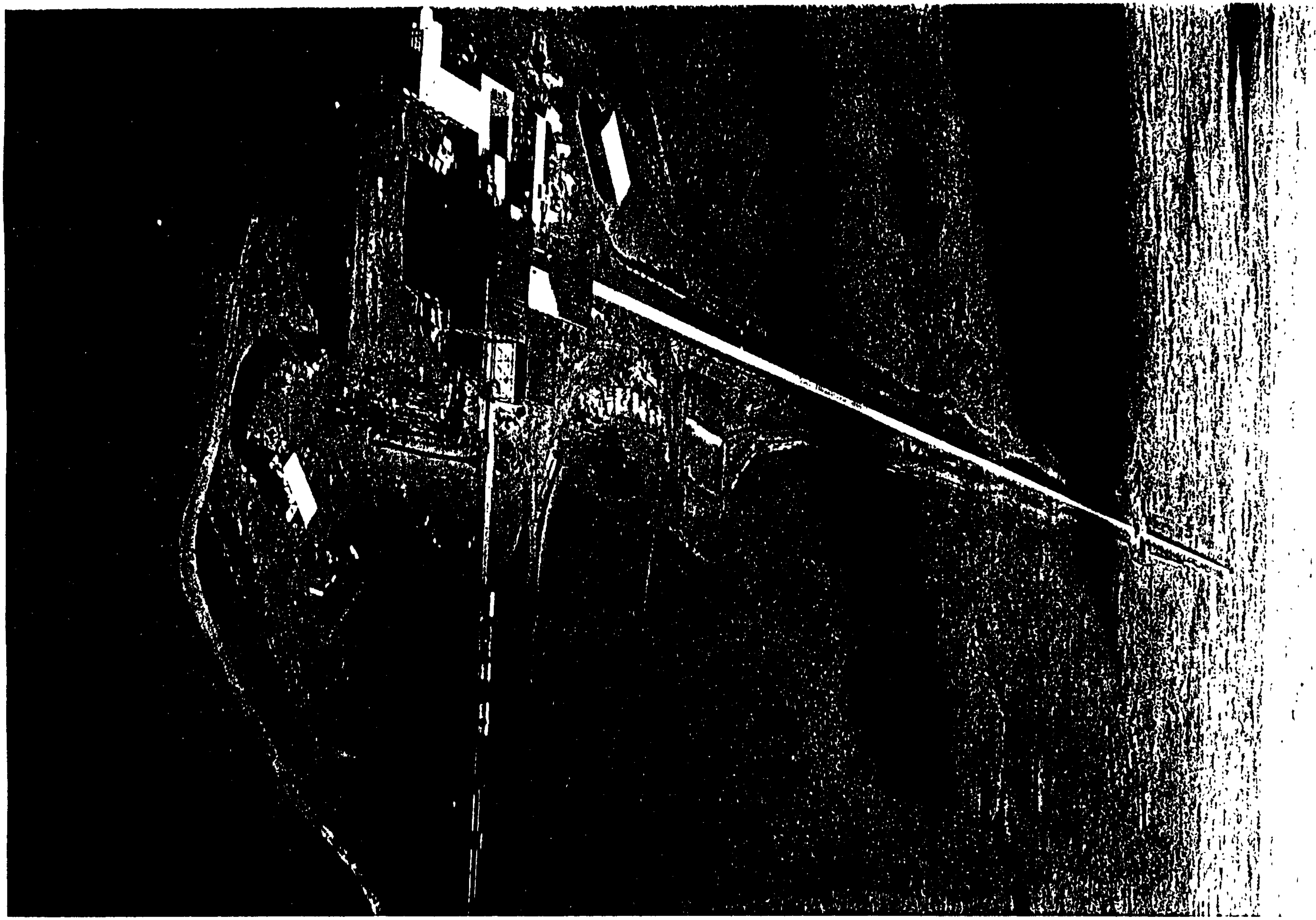

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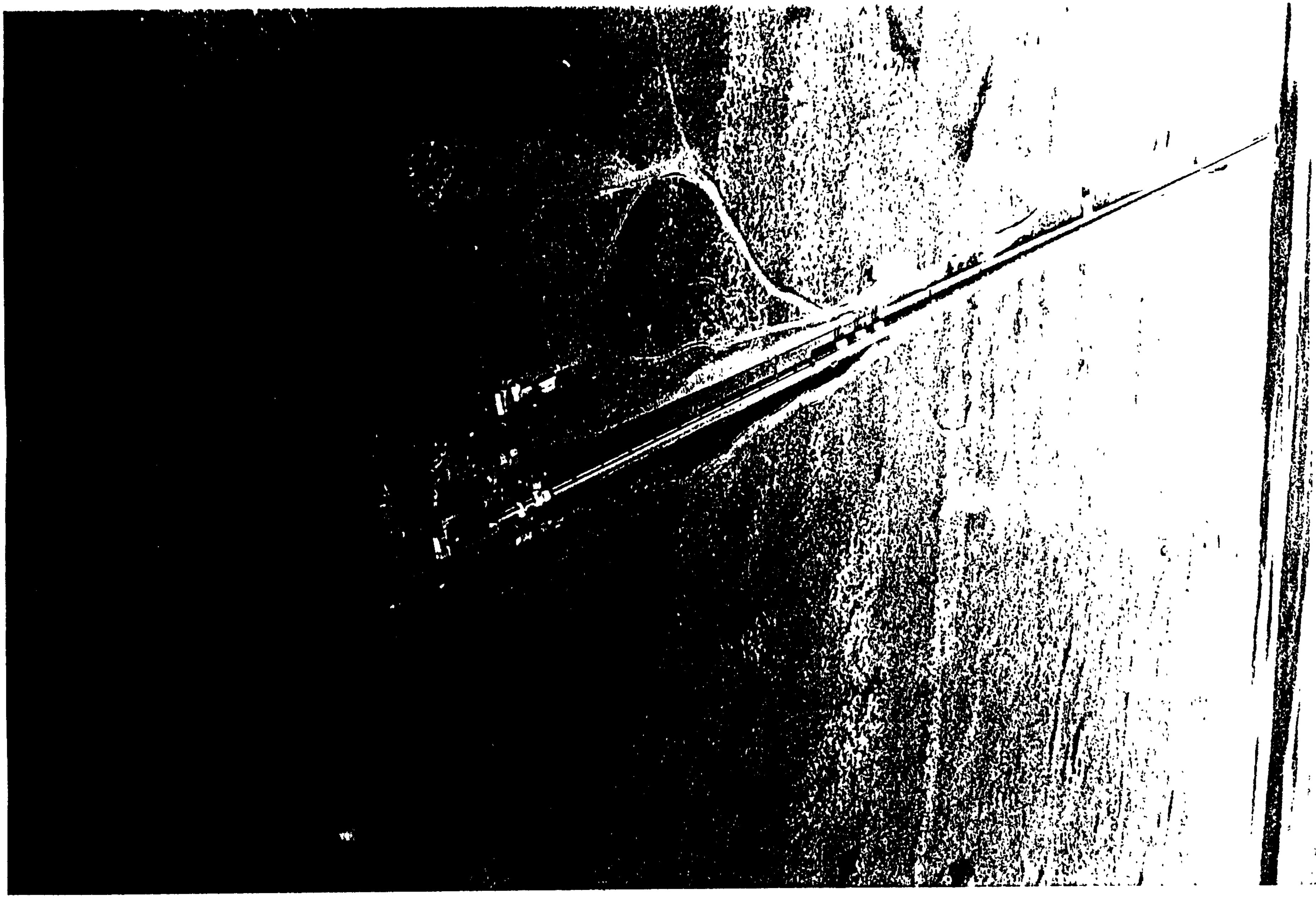

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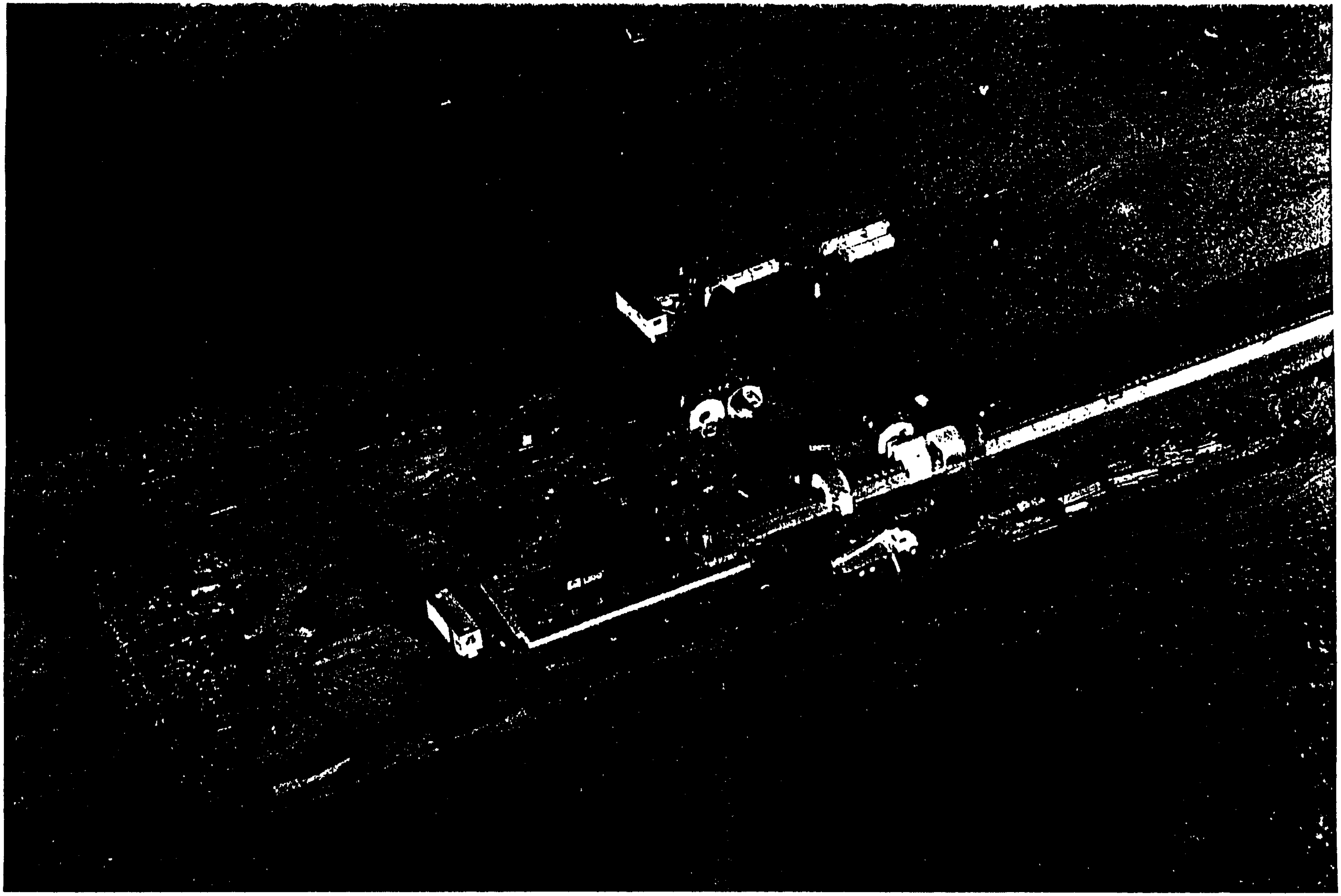

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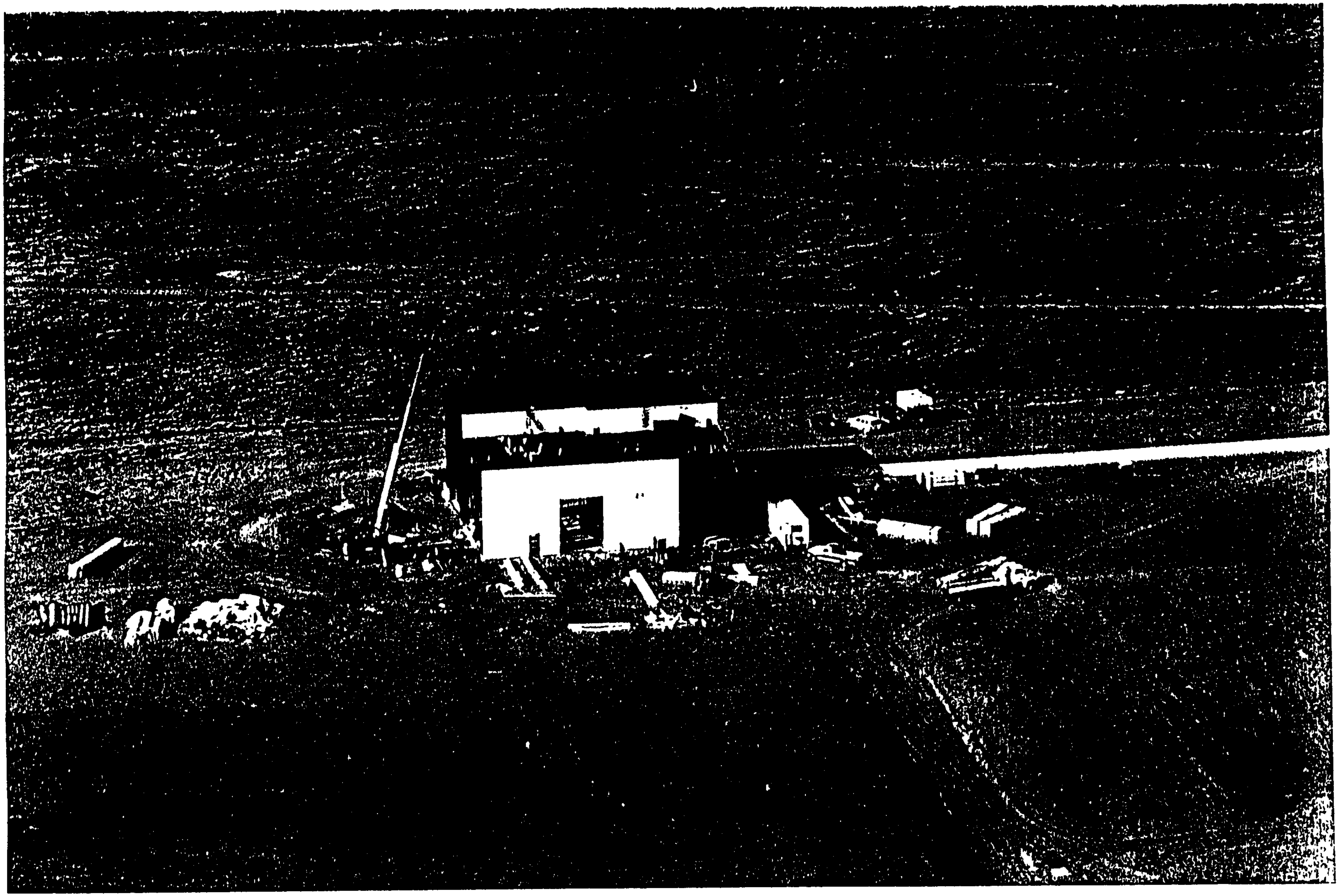

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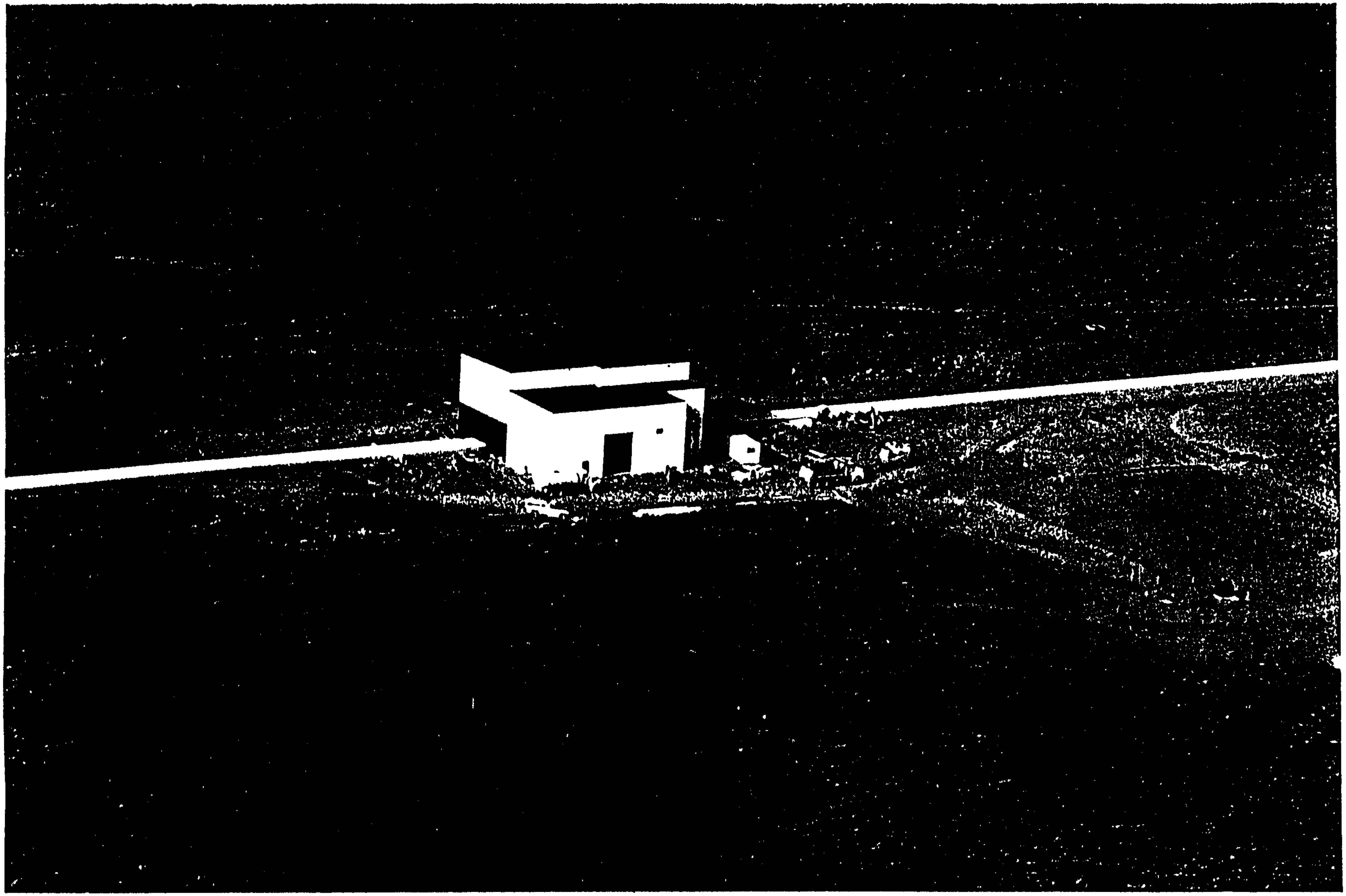

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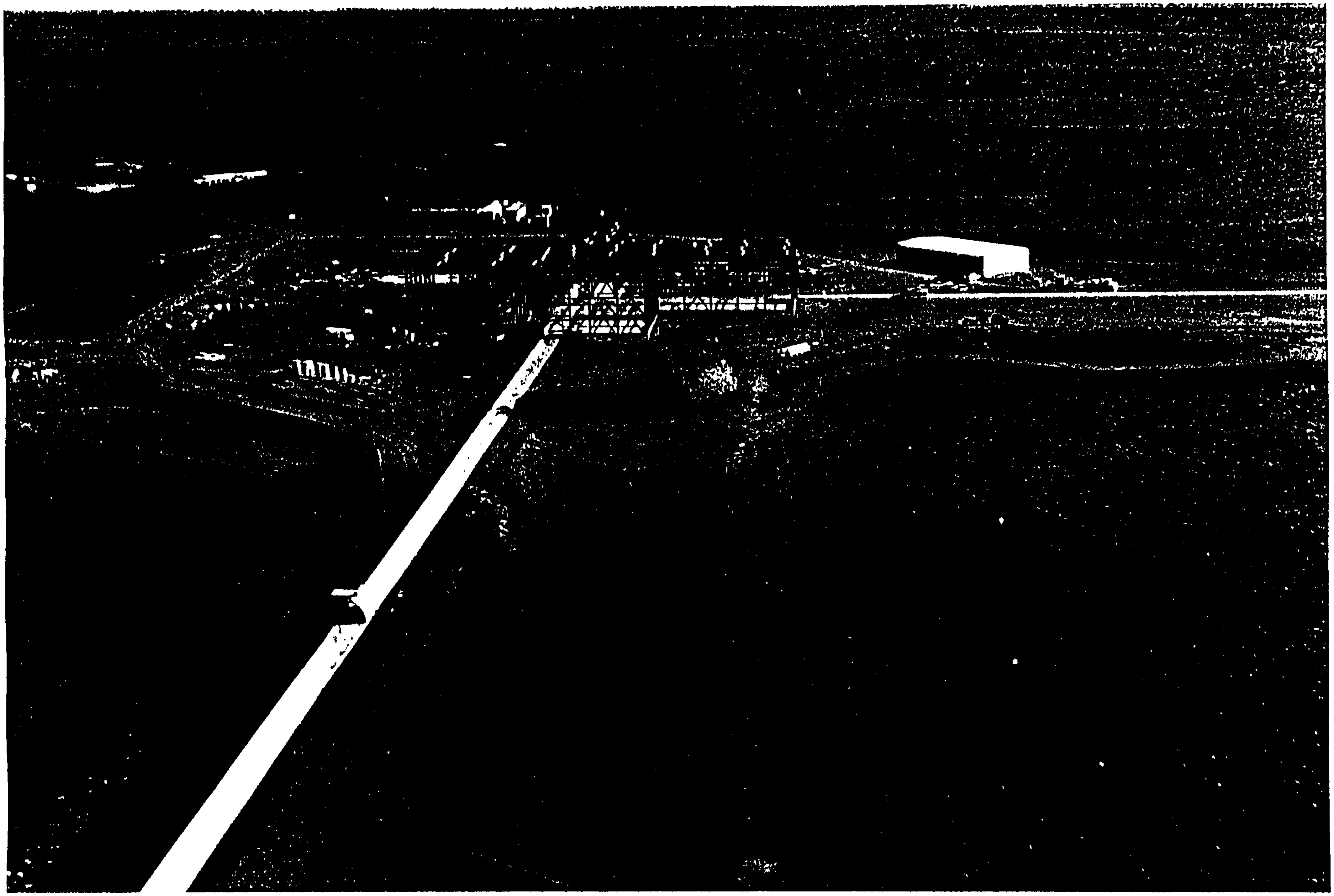

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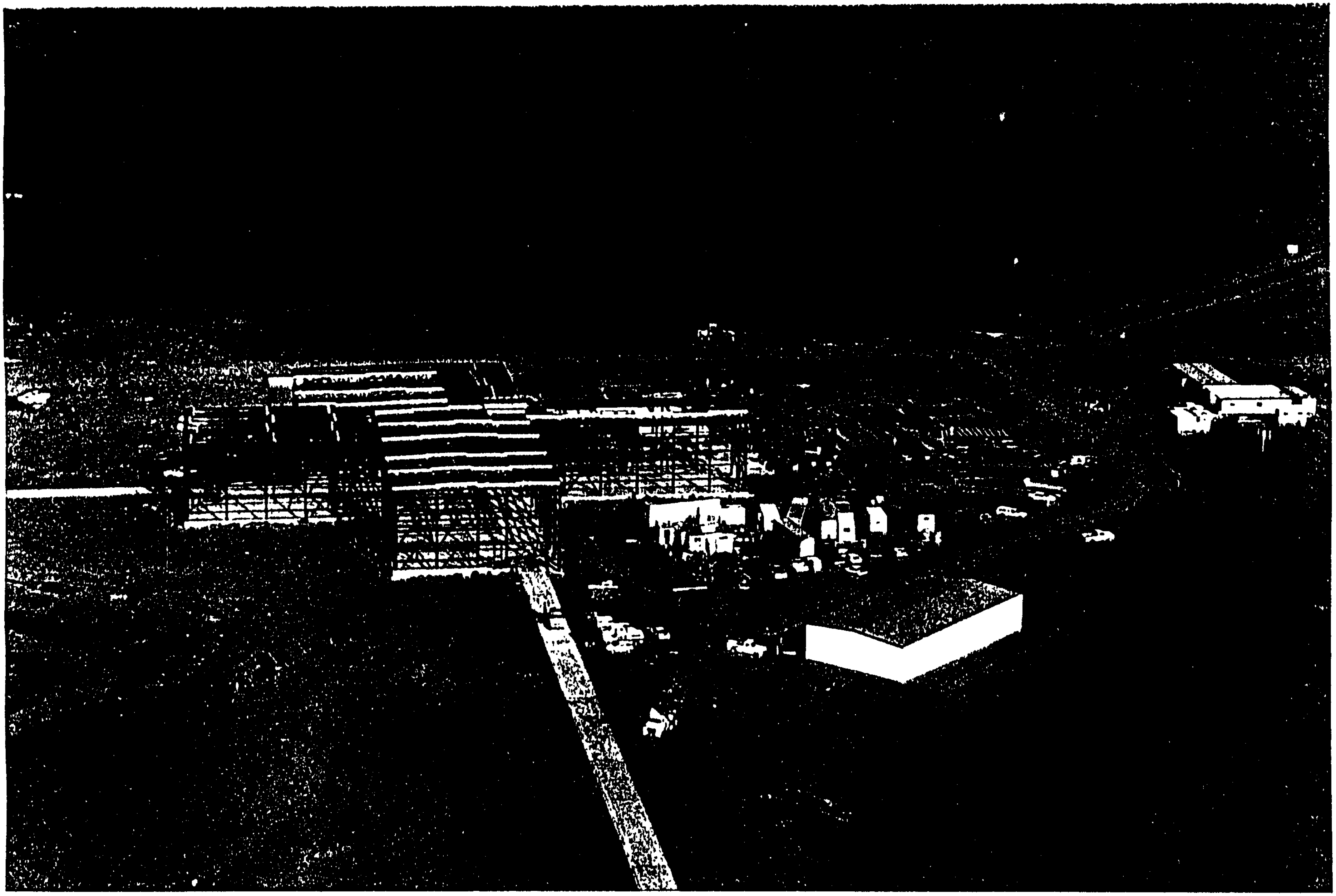

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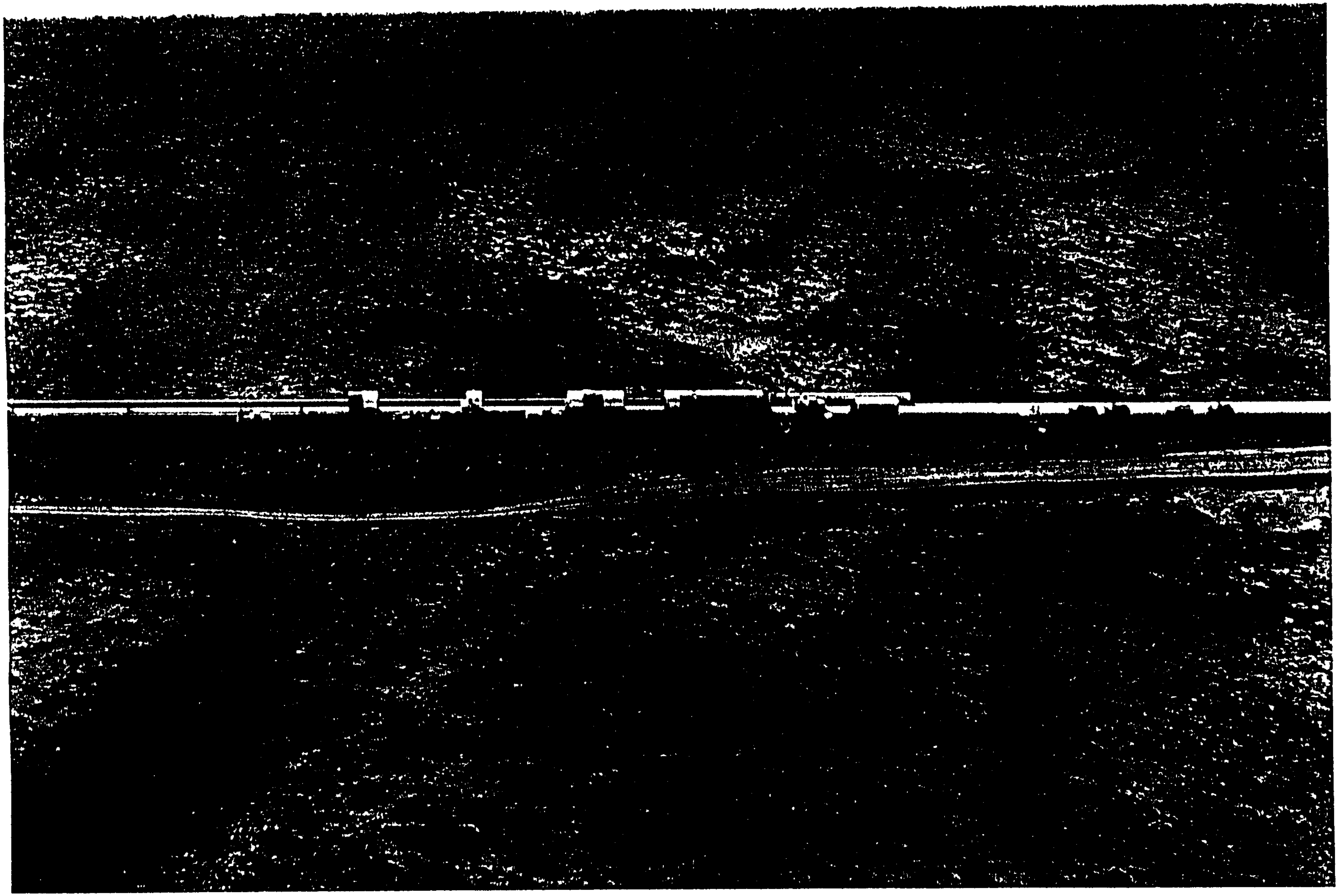

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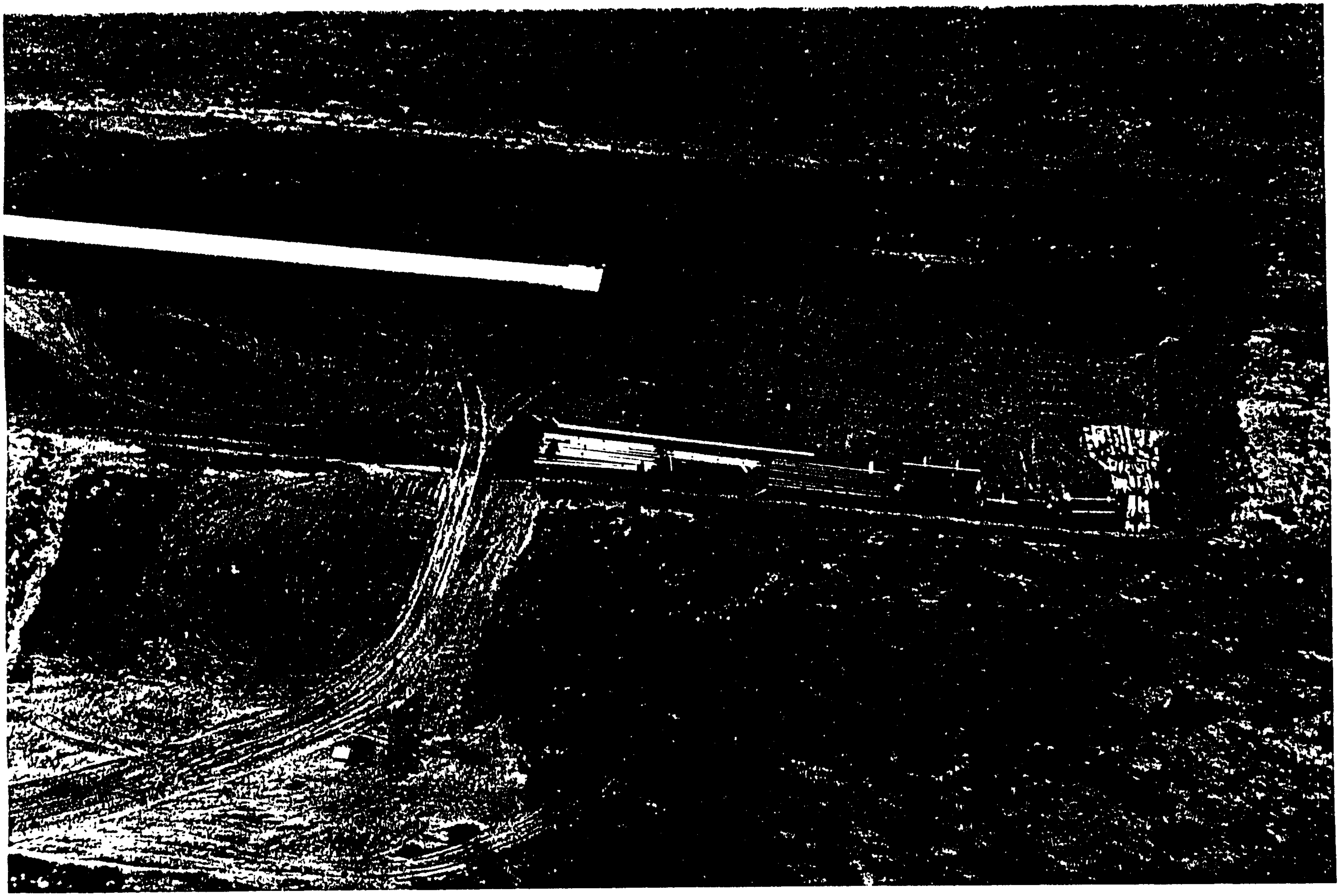

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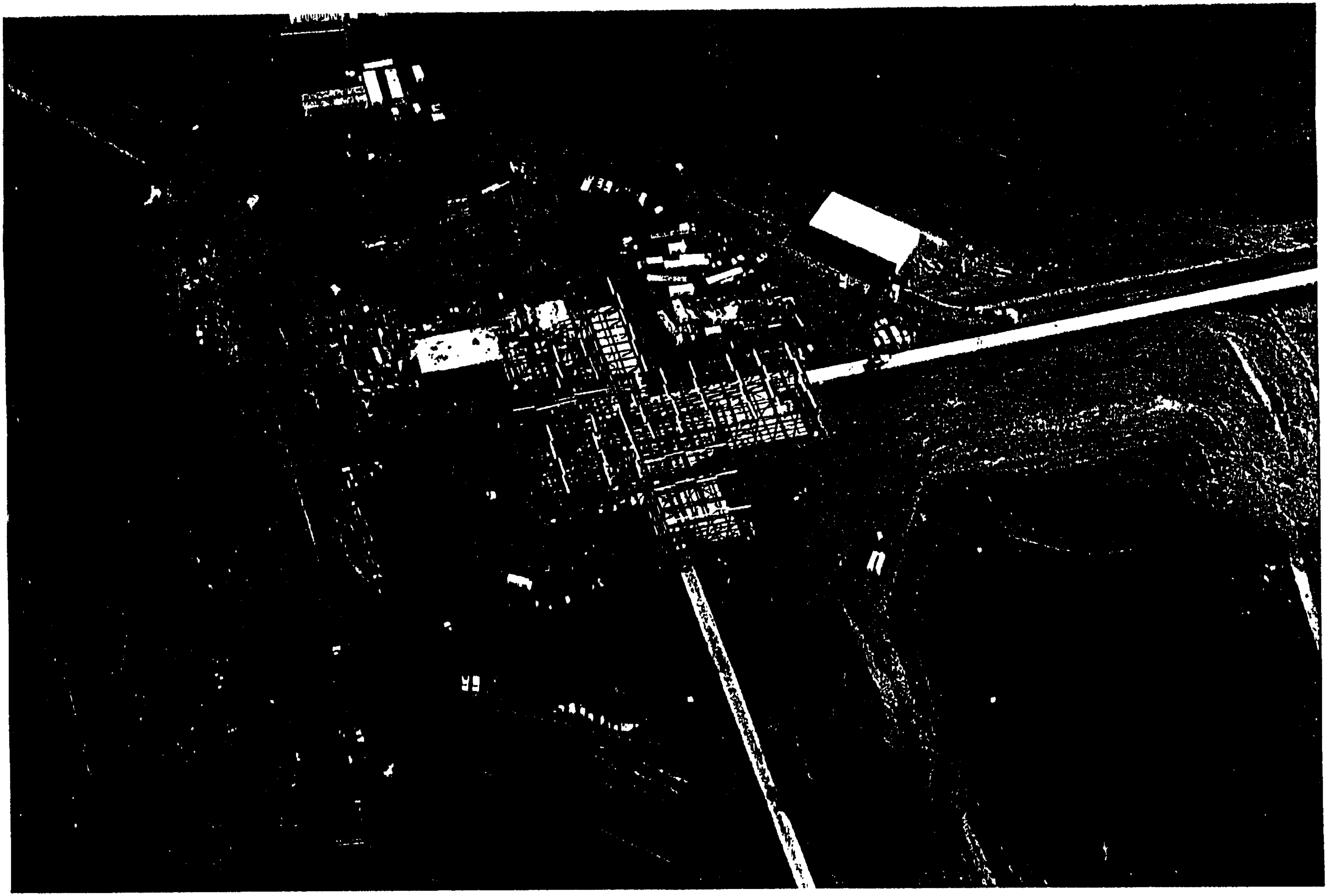

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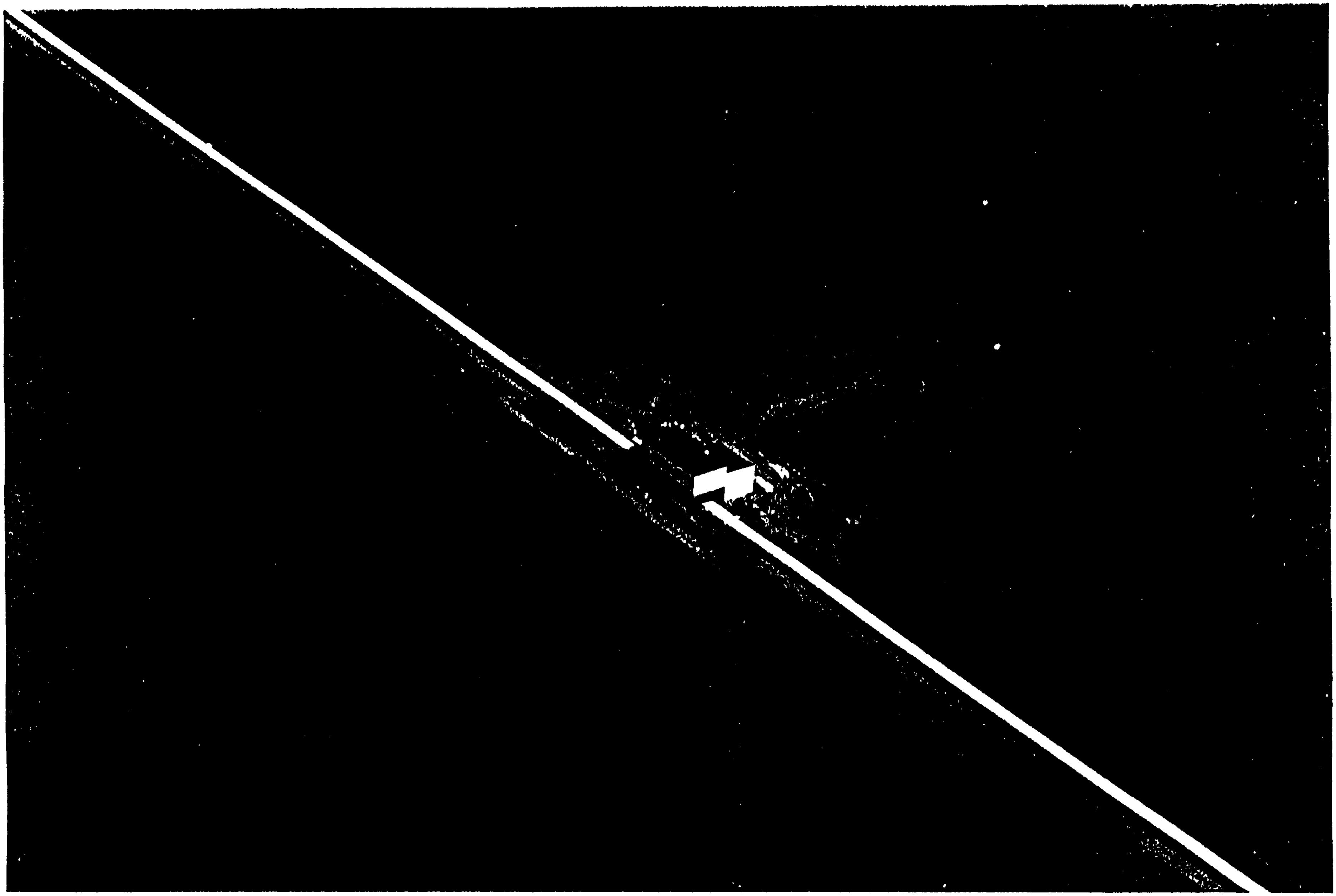

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MEMBERS OF THE LIGO GROUP AT MIT

Rainer Weiss
PAC Meeting, MIT - 12 June 97

Scientists	Peter Fritschel	David Shoemaker
	Gabriela Gonzalez	Daniel Sigg
	Alex Marin	Rainer Weiss
	Haisheng Rong	Michael Zucker
Visiting Scientist	Janet Houser (8/97)	
Engineers	Ralph Burgess (0.5)	Matt Smith
	Ken Mason	
Graduate Students	Brett Bochner	Peter Csatorday
	Shourov Chatterji	Brian Lantz
Undergraduate Students	Ken Chang	Sarah Veatch
Technical Support	Tom Evans	Ed Kruzel
Secretarial Support	Michael Richard (0.6)	Will Plummer (0.6)

CURRENT PROGRAM

- Interferometer Sensing and Control
  - ›› Length sensing and control
    - — R&D: Phase noise interferometer
    - — 1 micron interferometry
  - ›› Alignment Sensing and Control
- Detector system requirements
  - — Vacuum contamination measurements
  - — Scattering measurements
  - — Detector diagnostics
- Environmental monitor system
  - — Preliminary site/site correlation measurements
- FACILITIES
  - ›› Vacuum equipment scientific liaison
  - ›› Beam tube scientific liaison
  - ›› Scientific support to systems integration

FUTURE PROGRAM

- **COMMISSIONING AND INITIAL OPERATIONS**
- **OBSERVATION PLANNING AND DATA ANALYSIS**
- **DEVELOPMENT, TEST AND INSTALLATION OF ADVANCED DETECTOR SUBSYSTEMS AND ADVANCED DETECTORS**
- ISSUES
  - ›› MULTI SITE OPERATIONS
  - ›› LABORATORY RELOCATION
  - ›› ADDITIONAL FACULTY

INVOLVEMENT OF THE MIT COMMUNITY IN LIGO

- Physics, Mathematics and Electrical Engineering Dept
  - » Data analysis and astrophysics

Prof Edmund Bertschinger	Prof Maurice Van Putten
Prof Alan Guth	Prof Frederic Rasio
Prof Alan Oppenheim	Prof Gerald Sussman

- Dept of Material Science and Engineering
  - » Consultation on manufacturing and welding techniques
    - – Prof Tom Eagar
  - » Consultation on failure analysis and corrosion
    - – Prof Regis Pelloux
  - » Contamination studies in Surface Measurements Laboratory
    - – Auger, SIMS, XPS analysis

INVOLVEMENT OF THE MIT COMMUNITY IN LIGO

- Dept of Civil Engineering
  - ›› Consultation on LIGO concrete slab construction
    - — Prof Oral Buyukozturk
- Dept of Earth, Atmospheric and Planetary Sciences
  - ›› Consultation on LIGO alignment with the Global Positioning System (GPS)
    - — Prof Charles Counselman
    - — Prof Thomas Herring

MIT Group Transition to LIGO Operations Phase

M. Zucker

Interferometer Sense/Control Task Group

MIT Advanced Detector R&D

LIGO Physics Advisory Committee Meeting

12-13 June, 1997

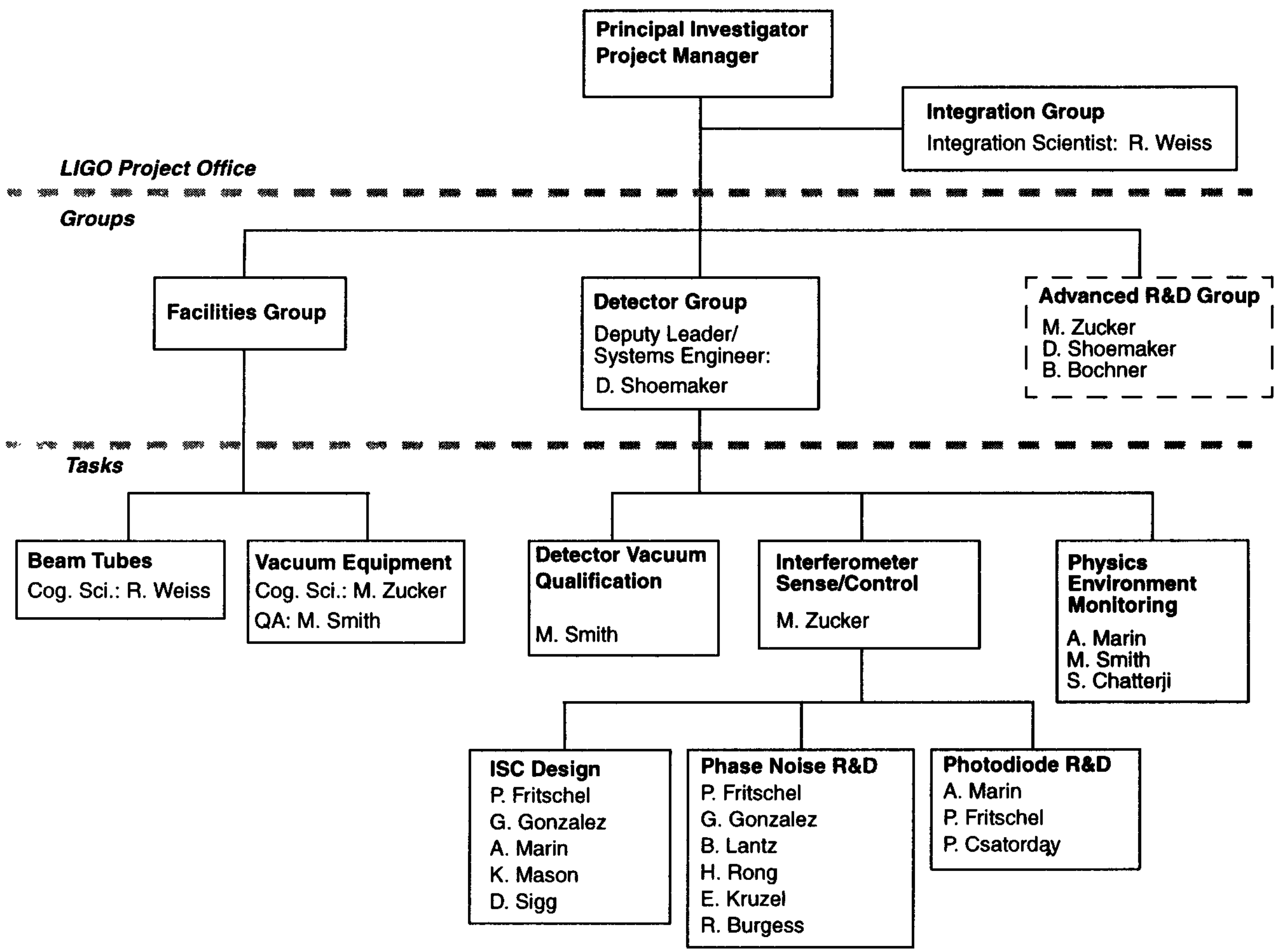
Massachusetts Institute of Technology

LIGO-G970105-00-M

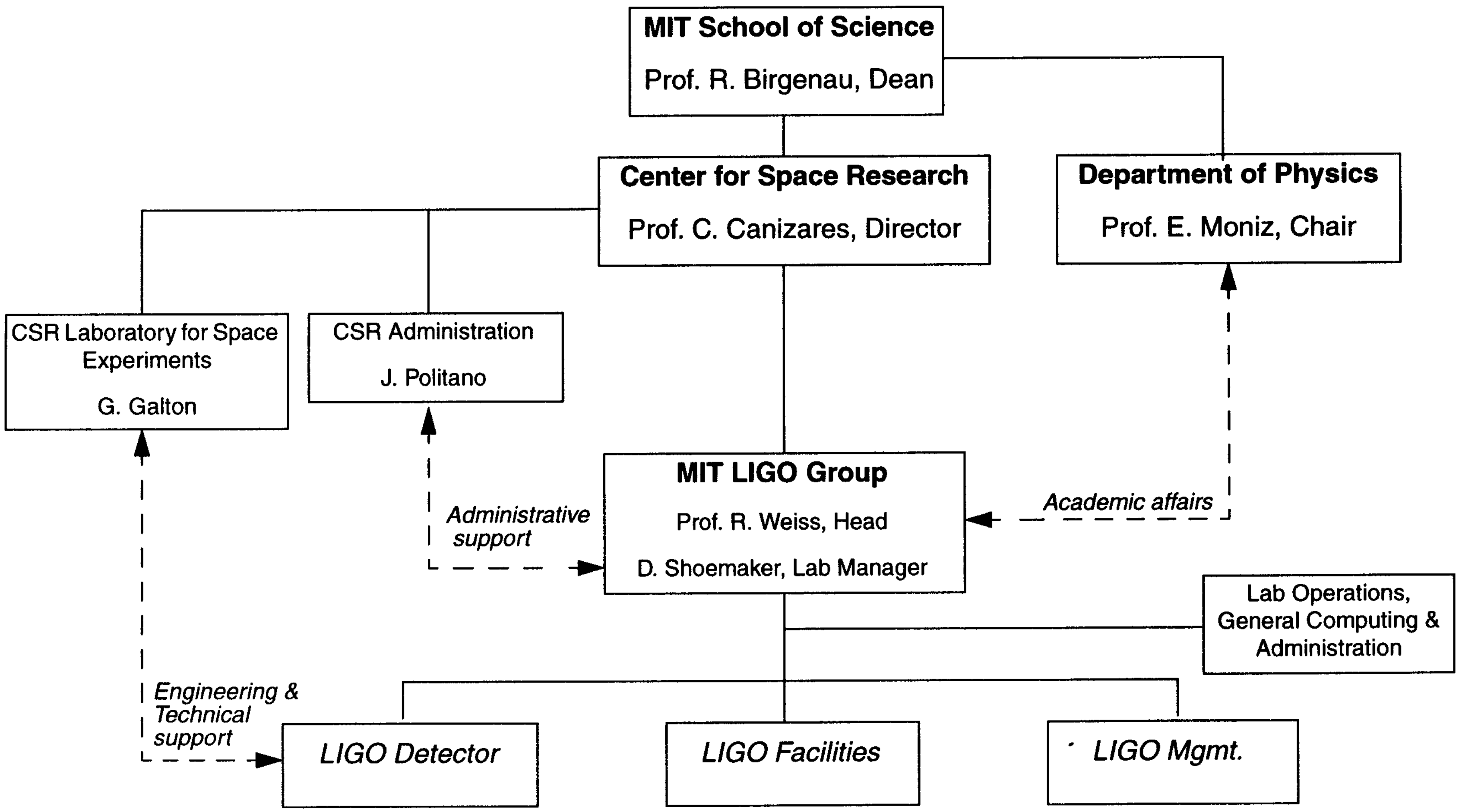
NOW: Current MIT activities for LIGO construction

- Project level
  - Facilities design/construction support (Weiss, Zucker, Smith)
  - Systems integration & management
    - > Project Integration Scientist (Weiss)
    - > Deputy Detector Group Leader/Systems Engineer (Shoemaker)
- Detector group
  - Detector R&D (PNI, Photodiodes, PEM sensors, ...)
  - Interferometer Sense/Control Design, Fabrication, Integration
  - Physics Environment Monitor Design, Fabrication, Integration
- Advanced Detector R&D
- Astrophysics & LIGO Data Analysis

Current MIT responsibilities: LIGO context

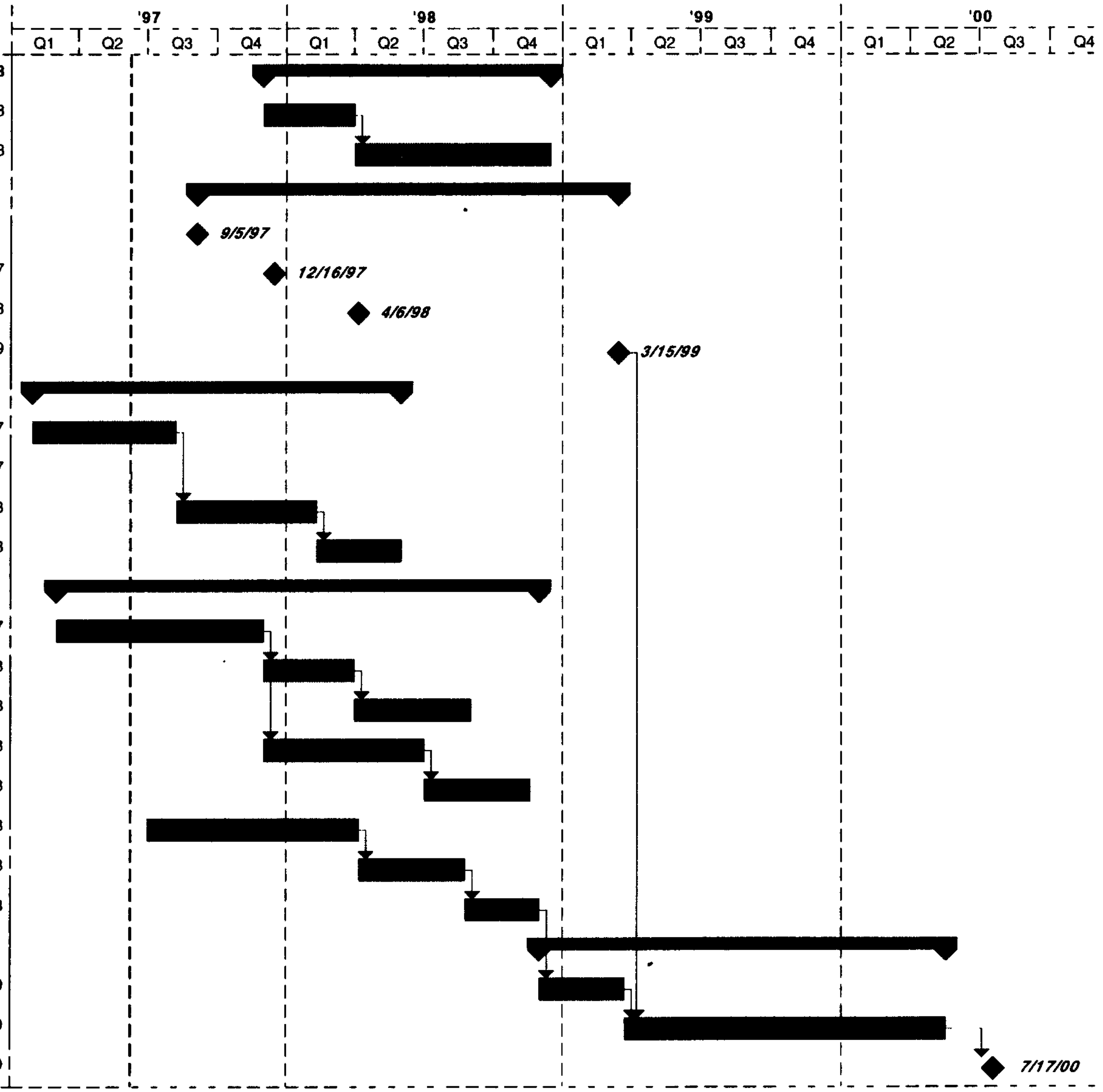


MIT Organizational Context



Near-term Schedule

ID	Task Name	Finish
1	**MIT Campus Lab Changes**	**Tue 12/15/98**
2	MIT Lab Move to NW17	Tue 3/31/98
3	Procure/Integrate New MIT Testbed F:	Tue 12/15/98
4	**Hanford Facility Milestones**	**Mon 3/15/99**
5	LVEA beneficial occupancy (WA)	Fri 9/5/97
6	Accept beam tubes (WA)	Tue 12/16/97
7	Accept vacuum equipment (WA)	Mon 4/6/98
8	BT Bakeout complete (WA)	Mon 3/15/99
9	**Detector PEM (Hanford)**	**Mon 6/1/98**
10	PEM Final Design	Thu 8/7/97
11	Field Tests/Correlation Analysis	Mon 6/9/97
12	Fab/Test	Mon 2/9/98
13	Installation	Mon 6/1/98
14	**Detector ISC (Hanford)**	**Mon 11/30/98**
15	ASC Final Design	Mon 12/1/97
16	ASC IAS Fabrication/Test	Tue 3/31/98
17	ASC IAS Installation	Tue 9/1/98
18	ASC WFS Fab/Test	Wed 7/1/98
19	ASC WFS Installation	Wed 11/18/98
20	LSC Final Design	Mon 4/6/98
21	LSC Fab/Test	Mon 8/24/98
22	LSC Installation	Mon 11/30/98
23	**Interferometer shakedown**	**Mon 5/15/00**
24	Recycled Michelson testing	Mon 3/22/99
25	Full interferometer testing	Mon 5/15/00
26	*Begin coincidence operations*	Mon 7/17/00



LIGO Integration & Commissioning

- Priority: *get LIGO I into operation*
- Focus is site-based
  - Installation, commissioning, diagnostics centered at Hanford & Livingston
  - "Pre-lockup" phase: all hands on one task (lead, follow or get out of the way)
  - "Post-lockup" phase: break out parallel investigations & concurrent tasks
- Campus facilities deployed mainly in support roles
  - Field equipment prep, cal, test (even repairs...)
  - Diagnostic modeling/simulation
  - "Integration Support R&D" ; rapid response to new findings
    - > First machine of its kind; expect issues needing experimental answers
    - > e.g., optical scattering, outgassing, PEM correlations, detector nonlinearity, surface analysis, vibration/acoustic modes, RFI tests, ... ?

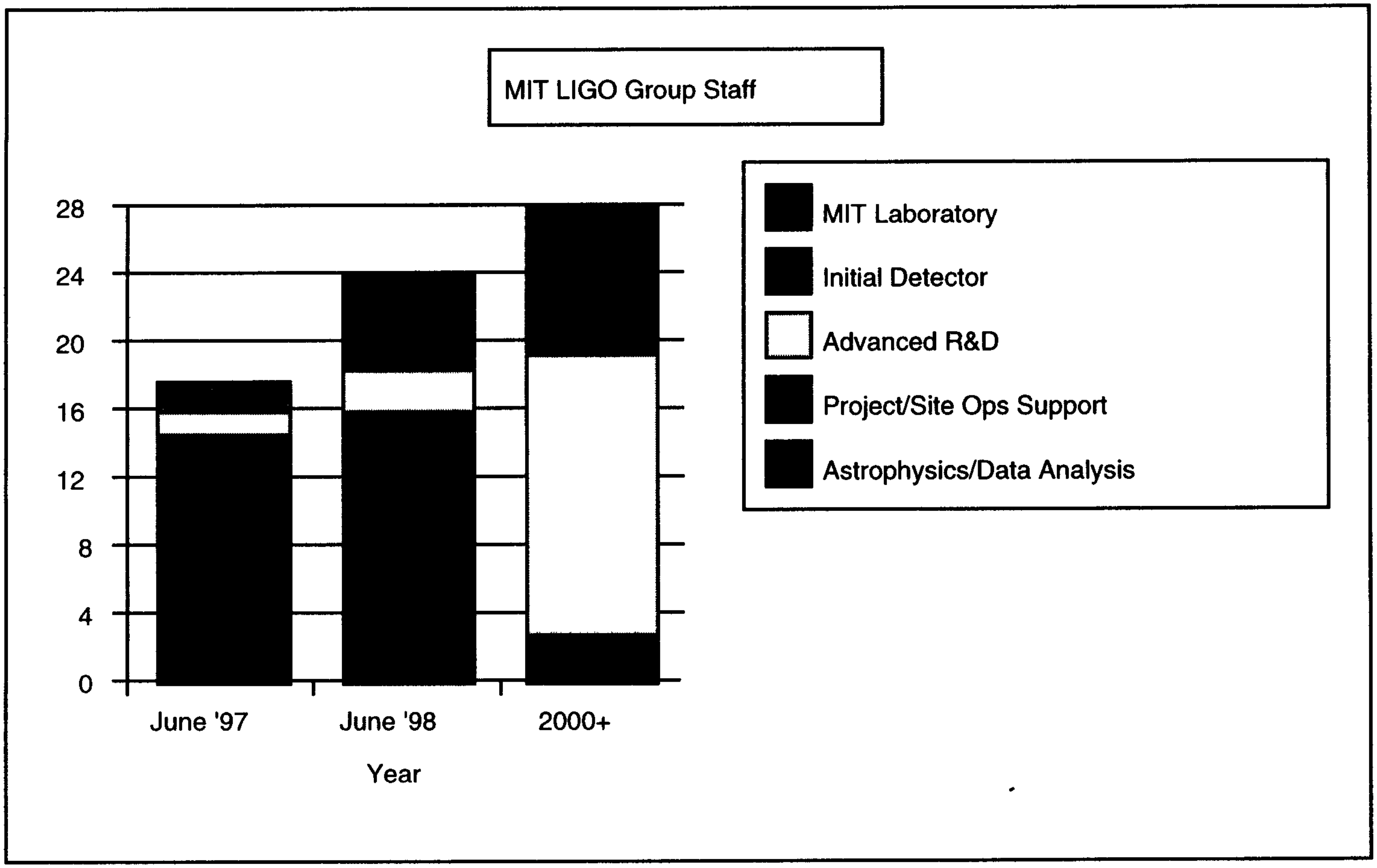
Remote Site/Campus Staffing Model

- Challenges:
  - involve students, postdocs, faculty in work which is fundamentally site-based
  - maintain ties & communication between site & campus resident personnel
  - help sites draw on campus resources, experience
- Response: staff rotations
  - terms interleaved so team members overlap, continuity preserved
  - projects comprise both site- and campus-based (or portable) components
- Goal: campus staff and resources fully integrated with Laboratory operations

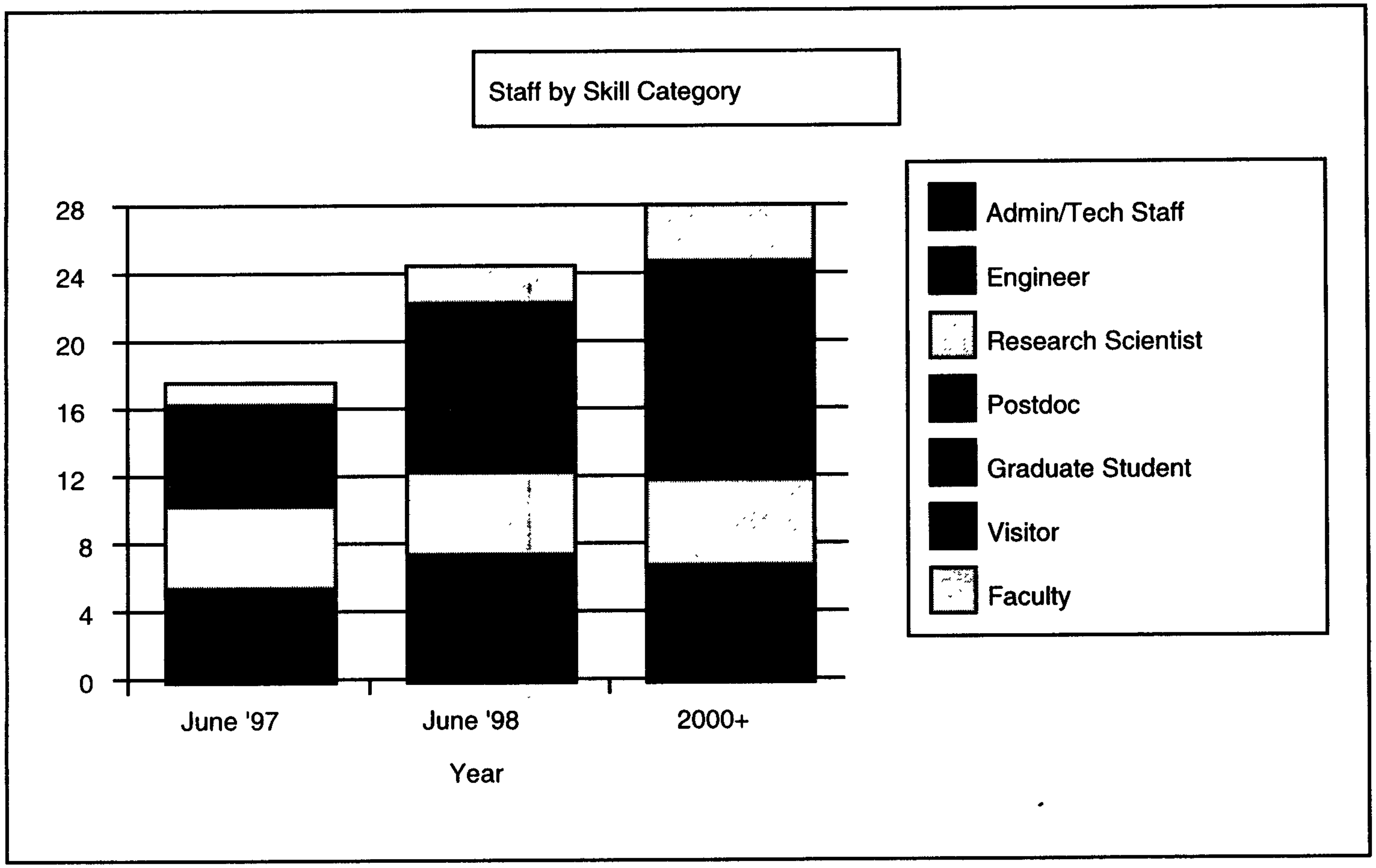
End State: Operations & Advanced R&D (as we'd like to see it)

- Data analysis...physics...discovery!
- LIGO Operations Support
  - Site staff rotations continue to support facility operations
  - Campus analytical, simulation, experimental detector support continues
  - Update/revisions/service for LIGO I systems & instrumentation
- Advanced Subsystem and Detector Development
  - Double Pendulum Suspension
  - Active Seismic Isolation
  - High-power Lasers & Optics
  - Advanced Detector Configurations

Group Focus by Task



Group Composition



MIT Lab Facilities and R&D Plans

PAC meeting 12 June 97
David Shoemaker

Recent history of R&D at MIT

- finishing contributions to initial LIGO
  - PNI: high sensitivity phase measurement, suspended interferometer
  - FMI: first complete ifo configuration test, length/alignment tested
  - photodiode, optical lever, Physics Environment Monitor prototypes
  - modeling covering both design and R&D
- some forward-looking work
  - dual-recycled interferometer studies
  - organization of suspension/isolation work in community

MIT lab moving

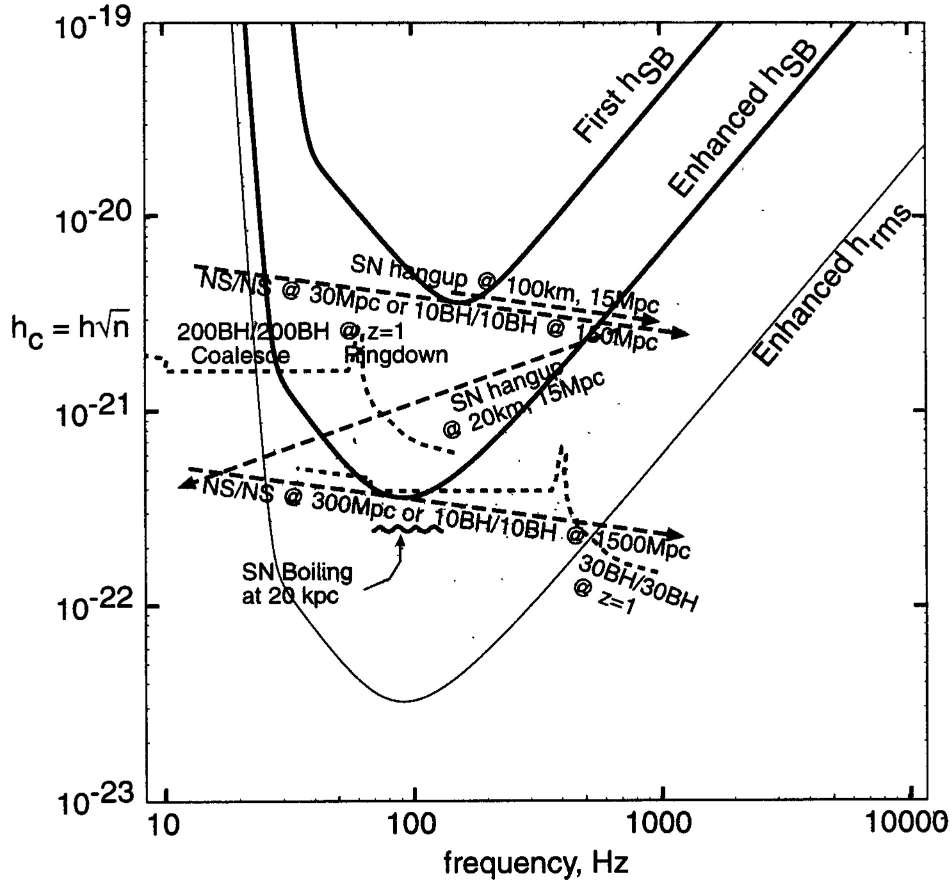
- building 20 to be torn down
  - 'the procreative eyesore'
- use opportunity to plan new facility for detector support, Adv R&D
  - allows present activities and some growth in staff (faculty)
  - enables LIGO to plan for future

Roles of Campus laboratories

Both MIT and CIT campus labs have similar roles

- campus support of commissioning and operation (Mike Zucker's talk)
  - modeling
  - service: contamination, scattering measurements
  - quick experiments to pursue ifo troubleshooting, e.g.,
    - tabletop optical measurements
    - mechanical transfer functions
- advanced R&D
  - advanced subsystems: near term
  - advanced LIGO: long term
    - participation/direction of the Ligo Science Collaboration
  - a focus for outside collaborators
- training of students
  - engagement in all of above

Choice of a research focus



Low Frequencies:

- longer observation of inspiraling binaries; larger bandwidth for impulsive events; better signal to noise for extraction of physics from waveform
- astrophysically most likely place to find sources (scaling arguments)
- changes in specific interests possible (probable!) after first discovery

Advanced R&D plan for LIGO targets this area

- collaboration an important aspect
  - GEO, Stanford, JILA, Syracuse, PSU, LSU, Moscow
- our plan designed to be complementary but with leading role

Requirements for a test interferometer

Ability to test optical interferometer as well as mechanical designs

- 40m over-subscribed; PNI example of work-in-parallel
- can specialize to low-frequency studies in a non-exclusive way
- sets length scale (~15 m), geometry ('L' configuration of vac sys)

Full-scale testing of mechanical components

- development: eliminates scaling of resonances, interference
- interaction of existing and added design elements
- qualification: final testing of hardware to be installed
- reduces down-time for LIGO ifo
- sets size scale to that of LIGO vacuum equipment

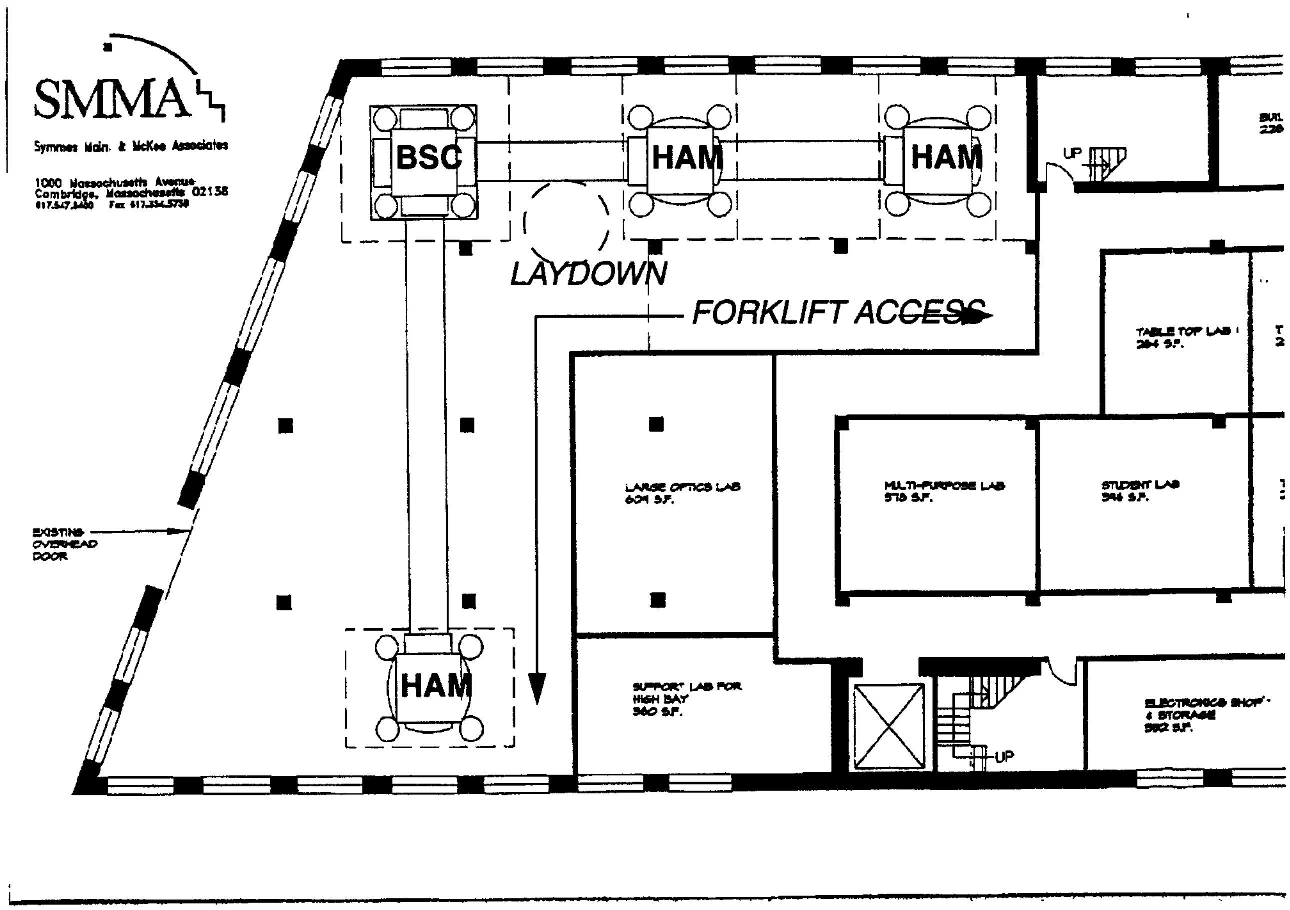
LIGO vacuum hardware

- assures right problems to be solved in design
- installation practice off-line from LIGO

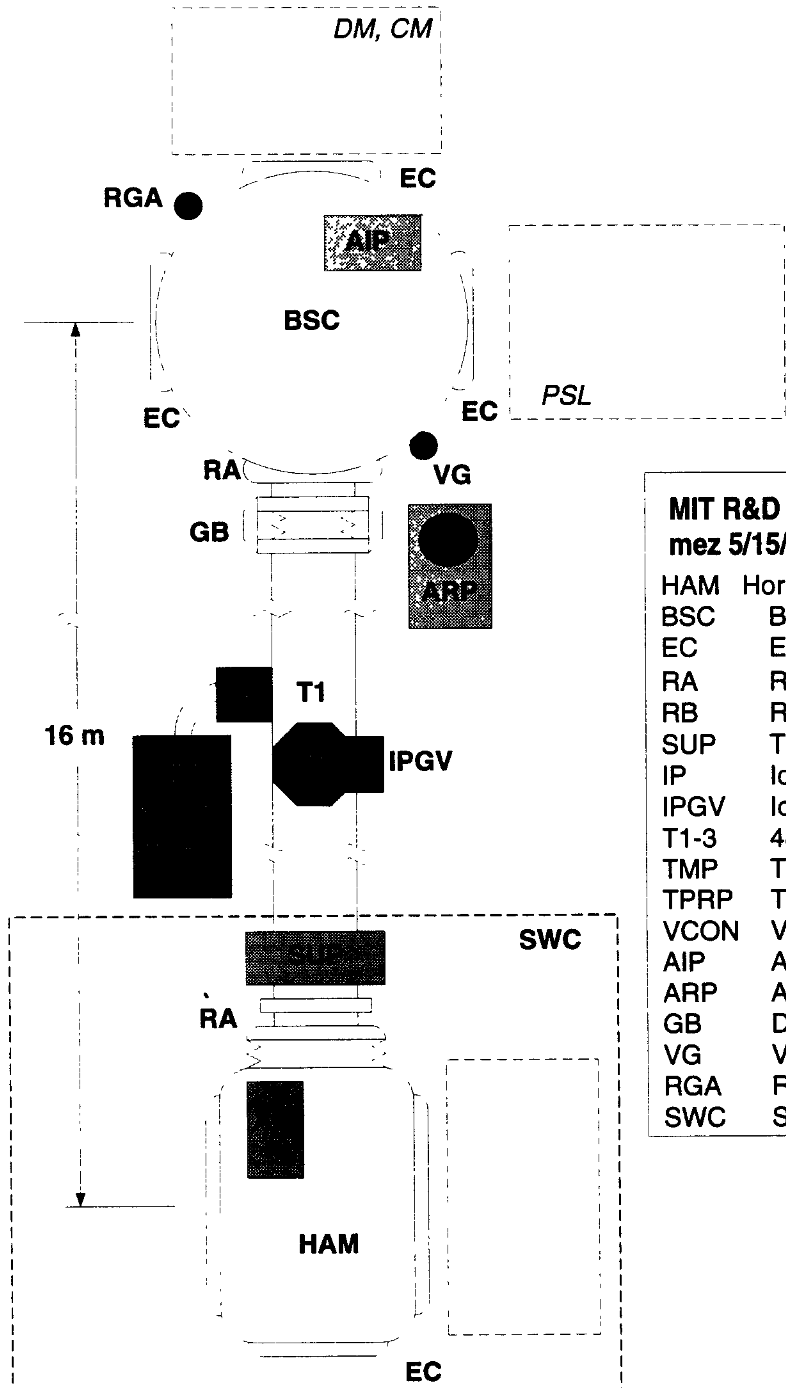
Supporting lab infrastructure

- physical: mech/elec shops, cleaning/prep, control, lightsource, storage
- visitors offices/labspaces
- human: manager, technicians, engineers

Test Interferometer



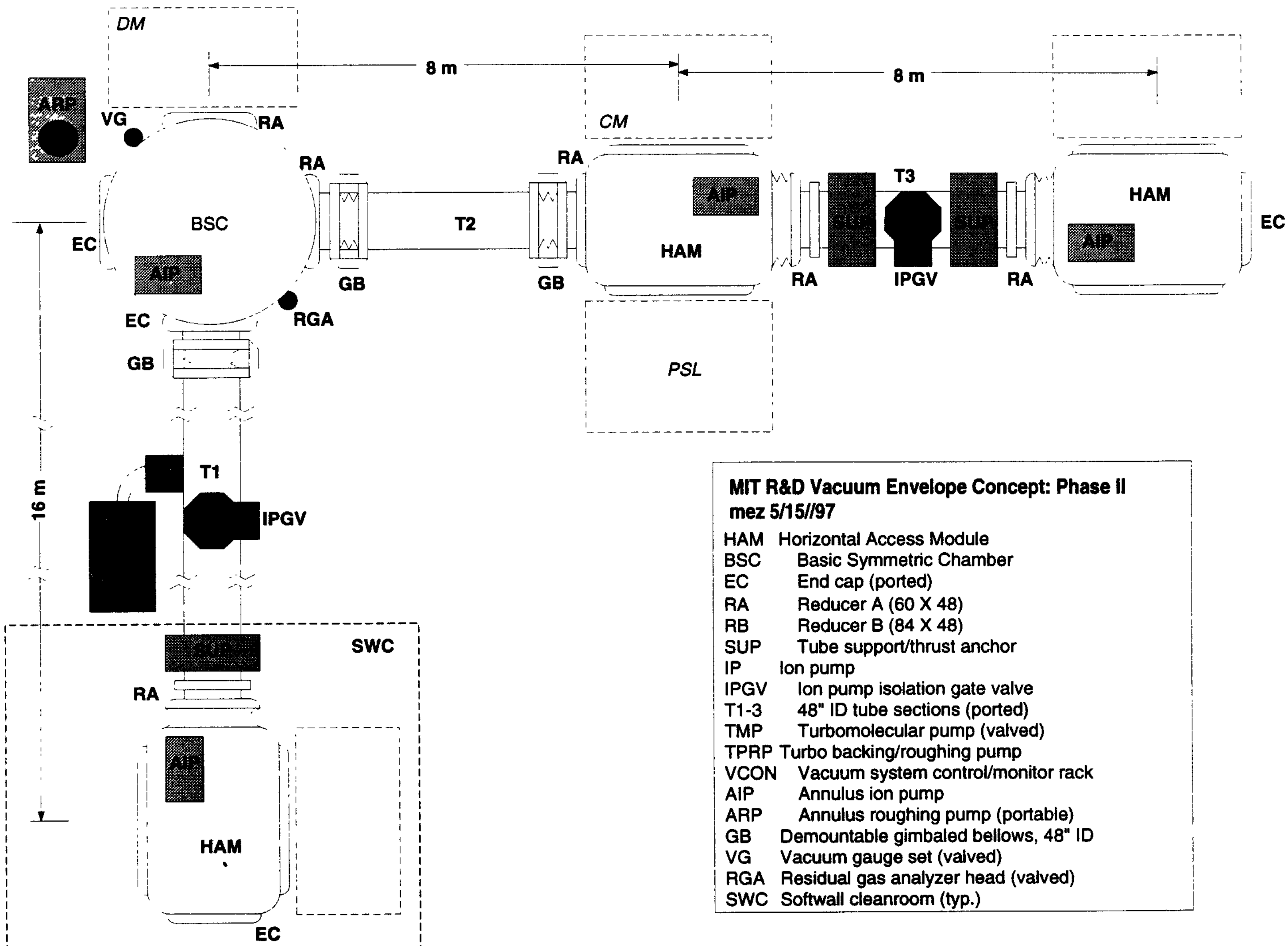
- First stage: HAM+BSC, 1.2 m x ~15m connecting tube; isolation stacks
  - › operational in fall 98
- Second stage: complete 'L' vacuum system
  - › operational in early 2001
- high-bay accommodating LIGO Vac Eq, supporting labs - details tomorrow



MIT R&D Vacuum Envelope Concept: Phase I
mez 5/15/97

HAM	Horizontal Access Module
BSC	Basic Symmetric Chamber
EC	End cap (ported)
RA	Reducer A (60 X 48)
RB	Reducer B (84 X 48)
SUP	Tube support/thrust anchor
IP	Ion pump
IPGV	Ion pump isolation gate valve
T1-3	48" ID tube sections (ported)
TMP	Turbomolecular pump (valved)
TPRP	Turbo backing/roughing pump
VCON	Vacuum system control/monitor rack
AIP	Annulus ion pump
ARP	Annulus roughing pump (portable)
GB	Demountable gimbaled bellows, 48" ID
VG	Vacuum gauge set (valved)
RGA	Residual gas analyzer head (valved)
SWC	Softwall cleanroom (typ.)

Phase 2



MIT R&D Vacuum Envelope Concept: Phase II
mez 5/15//97

HAM	Horizontal Access Module
BSC	Basic Symmetric Chamber
EC	End cap (ported)
RA	Reducer A (60 X 48)
RB	Reducer B (84 X 48)
SUP	Tube support/thrust anchor
IP	Ion pump
IPGV	Ion pump isolation gate valve
T1-3	48" ID tube sections (ported)
TMP	Turbomolecular pump (valved)
TPRP	Turbo backing/roughing pump
VCON	Vacuum system control/monitor rack
AIP	Annulus ion pump
ARP	Annulus roughing pump (portable)
GB	Demountable gimbaled bellows, 48" ID
VG	Vacuum gauge set (valved)
RGA	Residual gas analyzer head (valved)
SWC	Softwall cleanroom (typ.)

Research plan for the new installation

Target: 'Advanced Subsystem' suspension to be ready in 2003

(end of first data run)

- explicitly a double pendulum suspension
  - incremental changes in other mechanical subsystems
- R&D schedule calculated back from that date
  - '2007' advanced LIGO suspension in background until ~2003)

Significant steps in design process

- establishing requirements, interfaces, design constraints (~now)
- determining the state of the art, lessons from initial LIGO
- conceptual design (1998)
- construction and test of lab prototypes of aspects of design (1999)
- initial complete prototype testing (2000)
- test of final design (2001)
- qualification of suspensions to be installed (2002)

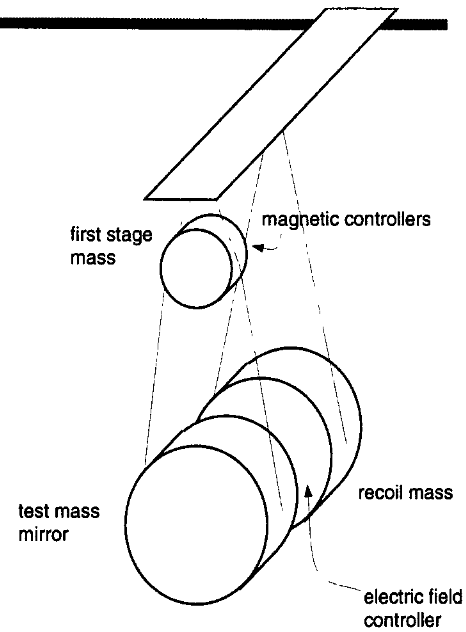
Guesses and Preferences

Once requirements are set,

- conceptual design subject to pet notions...

Ideas of a target design to pursue

- try to eliminate ALL actuation of the test mass
  - › concerns about damping of internal modes
  - › also, damping of pendulum
  - › requires two-loop suspension
  - › hard control problem



- aggressive active 'outside layers' required for above
  - › need to reduce seismic input such that BW < wire-resonance suffices
  - › external actuators with external sensing probably needed (STACIS-like)
  - › may also need damping of specific stack resonances (internal actuators?)
- 'monolithic' fused silica construction
  - › test mass: allows transmission through substrate
  - › sapphire end test masses, if polishing, coating, attachment resolved
  - › suspension fibers: improved Q, simplifies interface at test mass
  - › requires bonding techniques, under development
- upper mass with vertical leaf spring suspension
  - › required if seismic isolation of two stages to be realized
- avoid reaction mass
  - › adds complication in control dynamics; should not be needed for actuators

Specific activities at MIT

Requirements: mid-97 --> end 97

- requirements/interfaces/constraints based on initial LIGO
- visits to/from Glasgow (ongoing design of double pendulum)
- modeling of noise performance and control aspects
- staff: dhs, gg to spend a little time
- start search for experienced scientist to join effort

Design of configuration prototype: mid 98

- right number of masses, actuation points
- full scale, but Al masses, wire suspensions

Fabrication: end 98

Tabletop tests in air: early 99

- target: characterize LF XF, resonances, actuator
- michelson with one suspended element
- also iterations on design if needed

-- Phase 1 Test Interferometer in lab, shakedown completed Jan 99 --

Vacuum tests of a single suspension, one suspended element: June 99

- target: GW-band transfer function, pointing stability

Specific activities at MIT continued

Fabrication of two suspensions: Sept 99

- test of suspended cavity, 15m baseline: Sept 2000
  - in parallel with PNI suspended cavity
  - locking tests
  - noise tests to limit of laser stabilization using PNI suspended cavity
- refine design with results from research

Fabrication of 4 (6?) suspensions (modifs of prototypes?) March 01

-- Complete Test Interferometer in lab, shakedown completed March 01--

- installation of complete ifo
  - all double suspensions (at least on TMs)
  - either initial LIGO optical/readout configuration OR
  - incremental change, having been modeled/tested in advance

Test, noise and control characterization march 02

- also diagnostic readouts (wire/vertical)
- any data from optical configuration changes

fabrication of production suspensions Jan 03

installation/qualification of final suspensions Sept 03

Other R&D

Optics

- configuration modeling in conjunction with tabletop experiments at CIT, UFla
- small-scale advanced subsystems work
  - e.g., output mode cleaner
  - post-modulation readout techniques
  - modulation/detection/control tests on simplified configurations

Mechanical design

- active seismic reduction
  - in conjunction with new lab/MIT initiative
  - as part of suspension research
- possible alternative passive isolation studies: springs, resonance control

Some advanced topics

- too far away for specifics, but...
  - very aggressive seismic isolation (to gravity gradient limit at ~10 Hz)
  - optical configurations tolerant of high power/thermal focussing
  - means of producing very large test masses (Q, optics)
- ...all as coordinated within the Lab and with lots of collaboration

Facilities and Plans for R&D

Phase transition in LIGO

- from Project to Laboratory

Phase transition at MIT LIGO

- change in lab space
- opportunity to target activities and plan facilities to support them

First priority: Support initial LIGO installation and commissioning

- some of this is in fact R&D to respond to mysteries at the sites
- lots of it is people not in the lab in 98-99
- slows down labwork
- but: some continuity of labwork vital

Advanced R&D

- necessary for LIGO in the long term, important to scientific vitality of LIGO Lab
- MIT Test Interferometer and facility to play an important role
- significant investment for LIGO and MIT
- requires commitment of manpower and imagination from MIT Lab
  - responsibility to support activities from LIGO Lab, collaborators
- provides vital resource for advancing interferometer design
- provides focus for MIT Lab efforts, LIGO Science Collaboration as well

Data analysis

- The third piece of LIGO Lab activity: following talk by Peter Fritschel

MIT Program in Data Analysis

PAC Meeting, 12 July 1997

Peter Fritschel

- MIT group plans to be active in this area

  ›› current emphasis is on development of initial LIGO subsystems, but the ultimate goal of getting physics out of the instrument is main objective

- New faculty appointment expected, with a focus on LIGO astrophysics & data analysis

MIT: Data Analysis

Scenario for evolution of data analysis in first years of operation:

- Gaining a detailed understanding of the instrument performance
  - what is the quality of the data coming out of the instrument?
    - establishing the stationary noise, and the slow variations
  - what kinds of impulsive events are generated in the instrument?
    - catalog of transients
    - statistics & rates of transients
    - correlations with auxiliary channels; vetoes
  - explanation of the noise behavior: performance connected to known noise sources through modeling of the system
- Searching for anomalies (detection!) in the data
- Progress towards 'reduced data sets'– learning what data is necessary to store; what can be stored based on triggers
- *Initially, technical analysis and scientific analysis will be indistinguishable*

Connection with Current Work

- Interferometer Diagnostics & Online Data Analysis

  ›› data analysis will be intimately connected to the diagnostic system developed for the instruments, especially during initial operation

  ›› Role in diagnostics development

  ›› Interferometer Sensing & Control subsystem (ISC)

  - strain calibration & readout
  - readout of length & alignment DOFs that nearly all diagnostic functions will use

  ››Physical Environment Monitoring (PEM) system

  - source of many of the auxiliary channels used for correlations, vetos, etc
  - MIT has responsibility for designing, building, testing & installing the PEM

Data analysis & instrument characterization

- Results of data analysis indispensible to making improvements in performance
- Provides the clues for fixing problems with the initial interferometers
- E.g., influence on advanced suspension design

›› behavior of initial detector (2000-2001) can have a large impact on the focus of the advanced suspension development

❍ noise issues

❍ control issues

❍ model refinements

›› will benefit from a detailed understanding of interferometer behavior and comparison with simulations

Towards Astrophysics analysis

DATA ANALYSIS

Instrument Characterization

ASTROPHYSICS

Detector Advances

- Areas of prior experience
  - ›› stochastic background (N Christensen's thesis)
  - ›› periodic sources (J Livas' thesis)
  - ›› correlation vs. coincidence measurements (M Stephens)
- Area of primary interest:

Search for impulsive events of unknown waveform

- ›› will rely on understanding of instrument behavior
- ›› precedence: D Dewey's thesis on the 1.5m interferometer

Plans

- New postdoc hired (Aug 97 start) to work on diagnostics software
- Visiting scientists
- Faculty appointment
- Long term committtment:
  - 1-2 Scientists
  - 1 Postdoc, 1 graduate student

LIGO Laboratory Charter and Collaboration Formation Plan

Gary Sanders

Program Advisory Committee Meeting

June 12, 1997

Steps ...

- Aspen 1995 Workshop stimulates formation of LIGO Research Community
- LIGO Research Community forms
- NSF forms Panel on the Long Range Use of LIGO (1996)
- Report of Panel *(on NSF Web page)* calls for
  - » formation of LIGO Laboratory
  - » formation of LIGO Science Collaboration
  - » formation of strong LIGO Program Advisory Committee
  - » aggressive program of advanced R&D
  - » definition of needs for data analysis
  - » initiation of a Visitor's Program

Steps (continued)...

- PAC review of draft of LIGO Scientific Collaboration Formation Plan in January 1997.
- Draft presented at January 1997 Aspen Winter Conference generating vigorous debate.
- Lab Charter and revised draft for LSC posted on LIGO website March 5, 1997 and circulated by email bulletin to entire LRC.
- LIGO Oversight Committee provided review.
- All comments from all sources considered in revised documents posted prior to this meeting.

Results - PAC Transmittal Letter

Dear Barry:

Attached is the report of your Program Advisory Committee on the meeting of January 6 and 7. We found the meeting very informative, and thank you, the LIGO staff, and the spokesmen for the advanced R&D proposals for the excellent presentations.

The principal theme of the meeting was collaboration, a topic of great promise and urgency. We comment below on the plan for creating the LIGO Scientific Collaboration, and then review the specific proposals. Again, an overriding concern in our reviews is the extent to which a true collaboration is evident in the proposals. In many cases, we find this to be indicated only in a very sketchy, preliminary way. We emphasize the urgent need for the proposed researchers to develop, with the help of the LIGO staff and with those making related proposals, better defined plans for productive collaboration.

W. R. Frazer, Chair, LIGO Program Advisory Committee

Results - Plan for LIGO Science Collaboration

"The PAC endorses the statement in the Plan that "It is now prudent to form an overall LIGO Science Collaboration …", and we find the proposed Plan to be generally sound. We recommend, however, that the initial rules for joining the Collaboration be specified in the Plan. Subsequent modifications in these rules could be made by the Collaboration Council, with the concurrence of the Director.

<u>Proposed membership of the LIGO Science Collaboration (LSC):</u>

The members of the LSC are those individuals making major contributions to the project as formalized by MOU's with the LIGO laboratory management. Proposed additional members may be added at the recommendation of the Collaboration Council, with the concurrence of the Director. The criterion for membership should be evidence of intention to contribute significantly to the development, implementation, or data analysis of LIGO. …

Results - Plan for LIGO Science Collaboration

...Given the plan for an initial two year data run, followed by important enhancements to the project, the collaboration will comprise an initial LIGO I group and an extended LIGO group. The LIGO I group is composed of the members of the LSC who have made major contributions to the design and construction of LIGO and to the initial two year data run and would be the authors of the results coming from these data. The extended LIGO group, based on their contributions to the enhanced experiment, would be authors of the subsequent results.

The LSC should be led by a spokesperson. We endorse the description of the selection process and length of service in the Plan. The spokesperson would represent the collaboration to the laboratory management, be responsible for communication within the collaboration, and have a role in enhancing the coherence and focus of the extended LIGO technology development. Other special areas of responsibility should be either specified or clarified with the LSC Collaboration Council."

LSC Formation Plan Changes

- LSC reporting to Directorate narrowed to observational physics talks and publications
- Membership - minimum institutional group size is 3
- Meeting set to end Charter period (Aug. 15, LSU)
- LIGO I data becomes public two years after collection

Plan now published and many MOU's and Attachments are being negotiated

LIGO Laboratory Charter Changes...

- Relationship to LIGO Project Management Plan defined
- Oversight Committee charge and role better defined
- LSC website hyperlinked and possible formation of other collaborations acknowledged
- How PAC advice will be used by Directorate is stated more clearly
- Executive Committee membership broadened beyond Group Leaders to include all Caltech and MIT professorial faculty

LIGO Laboratory Charter Changes

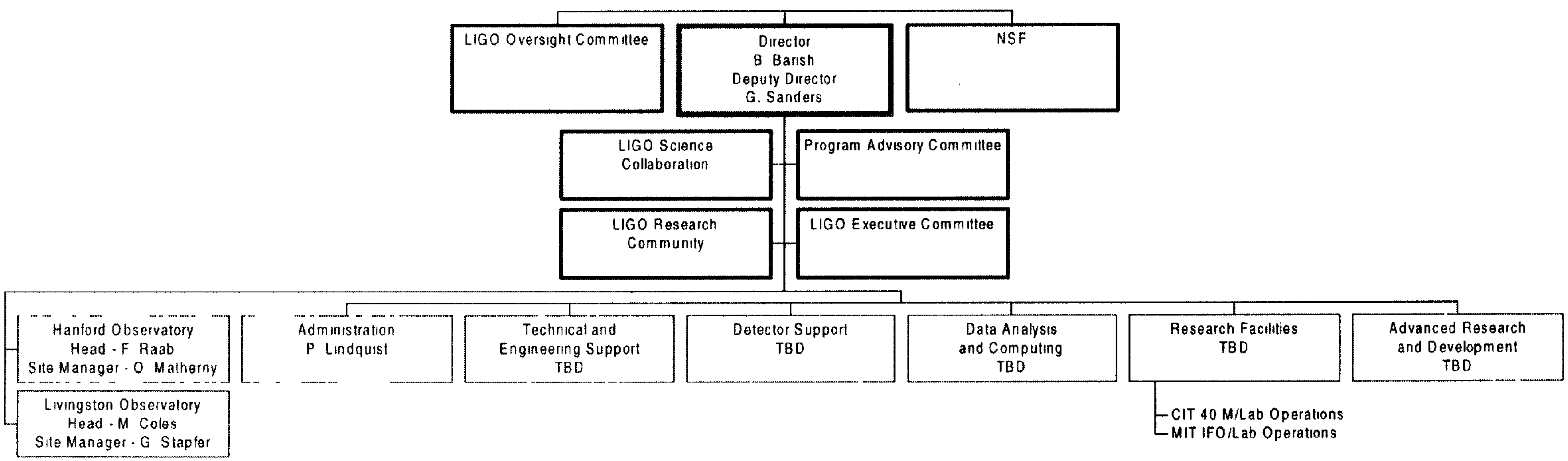
- Visitor's Program can be "bidirectional"
- Functional group definitions tightened and funding sources defined
- ES&H section streamlined
- ES&H reporting to Directorate specified

Omitted Suggestions

- Some policies and definitions for LSC left "fuzzy" for later definition by Collaboration
- CIT-MIT balance in Lab not addressed by rule
- Lab functional groups not forced to be orthogonal
- LSC not explicitly designed to cover far future beyond first decade, nor was LIGO I separated out as proprietary
- LIGO I membership not opened to all collaborators in LSC

LIGO Laboratory

LIGO LABORATORY ORGANIZATION



Actions Ahead

- NSF Approval of Lab Charter
- LSC Formation Meeting mid-August at LSU
- Many MOU's and Attachments Being Negotiated
- "Development Groups" Being Formed
  - » Minutes of Isolation Group on LIGO website

LIGO Data Analysis System

White Paper Overview

A.Lazzarini

12 June 97

LIGO PAC Meeting

Cambridge, MASSACHUSETTS

LIGO Data Analysis System

Paper presents an implementation approach to meet requirements for LIGO I searches:

- Astrophysical searches
  - Planned
  - Expect the unexpected....
- Data stream characteristics
  - Broadband (audio band; 6 octaves; 2 decades)
  - No (immediate) directionality inherent in data - non steerable antenna
  - Low SNR environment -- unique to LIGO (omnidirectional; weak)
  - Many ancillary channels -- potentially high total data rates; low GW data rates -- NEED to IDENTIFY automated REDUCTION PROCEDURES

LIGO Data Analysis System

- On-line component
  - ›› Design targets planned searches motivated by astrophysics
  - ›› Detection of compact mass binary inspiral used as a benchmark to determine the on-line capacity requirements -- other searches appear less demanding at this time
  - ›› Diagnostics supported through commissioning and into operations
    - Rapid access to data for decision-making and debugging - commissioning phase
    - Toolbox for signal processing analysis
      - **transfer functions**
      - **cross-spectral correlations, coherence functions & regressions**
  - ›› Data reduction/compression
  - ›› Unexpected physics -- restructure search strategies/approaches can be accommodated through flexible hardware choices

LIGO Data Analysis System

- Off-line component
  - ›› Approach seeks to maximize future expendability, access to resources, and availability
  - ›› LIGO will collaborate with Caltech's Center for Advanced Computing Research to set up a LIGO Data Analysis Center within CACR
    - Shared resources - personnel & hardware
    - Research on challenging analysis problems, database management
    - Exploit availability of latest technologies
    - Forces a commitment to analysis software standardization for portability
  - ›› Provides enhanced data analysis capability for LIGO I
    - Deeper, refined searches
    - Searches not feasible or not necessary on-line
    - Experimentation with algorithms, techniques, etc.
    - Reduction of data sets for long-term archival
  - ›› Data analysis system software tools will be available using web-browser based paradigm (implemented for SAR project JPL/ Caltech -- http://www.cacr.caltech.edu/~roy/sara/index.html)
    - Software design & implementation choices
  - ›› Exploit communications infrastructures to provide (transparent) access to archive for remote users

LIGO Data Analysis System

- Software Development
  - Prototyping phase
    - Algorithm development/validation/quantification
    - User interface prototyping
    - Web-browser paradigm for broad access
    - Client-server configuration launch analysis tasks on host machine(s) and retrieve results
  - Simulation environment meshed to analysis through data representation (data frame format) and language standardization (C++)
  - Standardization choices
    - UNIX operating system
    - Object oriented language -- C++; ANSI standard due soon
    - Commitment to standards (ANSI/POSIX) for cross-platform portability
    - Configuration management using concurrent version control (UNIX environment)

LIGO Data Analysis System

- LIGO Wide Area Network establishment
  - Provides LIGO intra-Laboratory communications:
  - Campus resources -- libraries; procurement, software resources, databases and data archives, video conferences, ...
  - Working with DOE and LSU to ensure access for LIGO to local resources/infrastructure at remote observatories.
- Cost projections
  - Capital investment at observatories to be provided through construction funding
  - Operational cost of WAN/off-line computing institutionally shared and funded through LIGO Laboratory operations

Issues

- Data preprocessing & reduction is required to produce a manageable archive
  - Calibration;
  - Regressing out instrumental effects;
  - Data QA;
  - Must be done correctly if raw data tapes are recycled...
  - BIG job, requiring dedicated scientific personnel
  - At observatories? -- Most of the instrumental understanding
  - At archive? -- Most of the hardware, staff, resources
- Archival
  - How much?
  - How long?
- Developing a flexible, efficient software analysis environment
  - Responsive to diagnostics needs
  - Responsive to unexpected discovery
  - Capable of cost-effective maintenance
  - C++ is foreign to most of the LIGO science team -- big learning curve
  - C++ is choice for large-scale project development -- separation of programming expertise from scientific expertise -- is this wise?

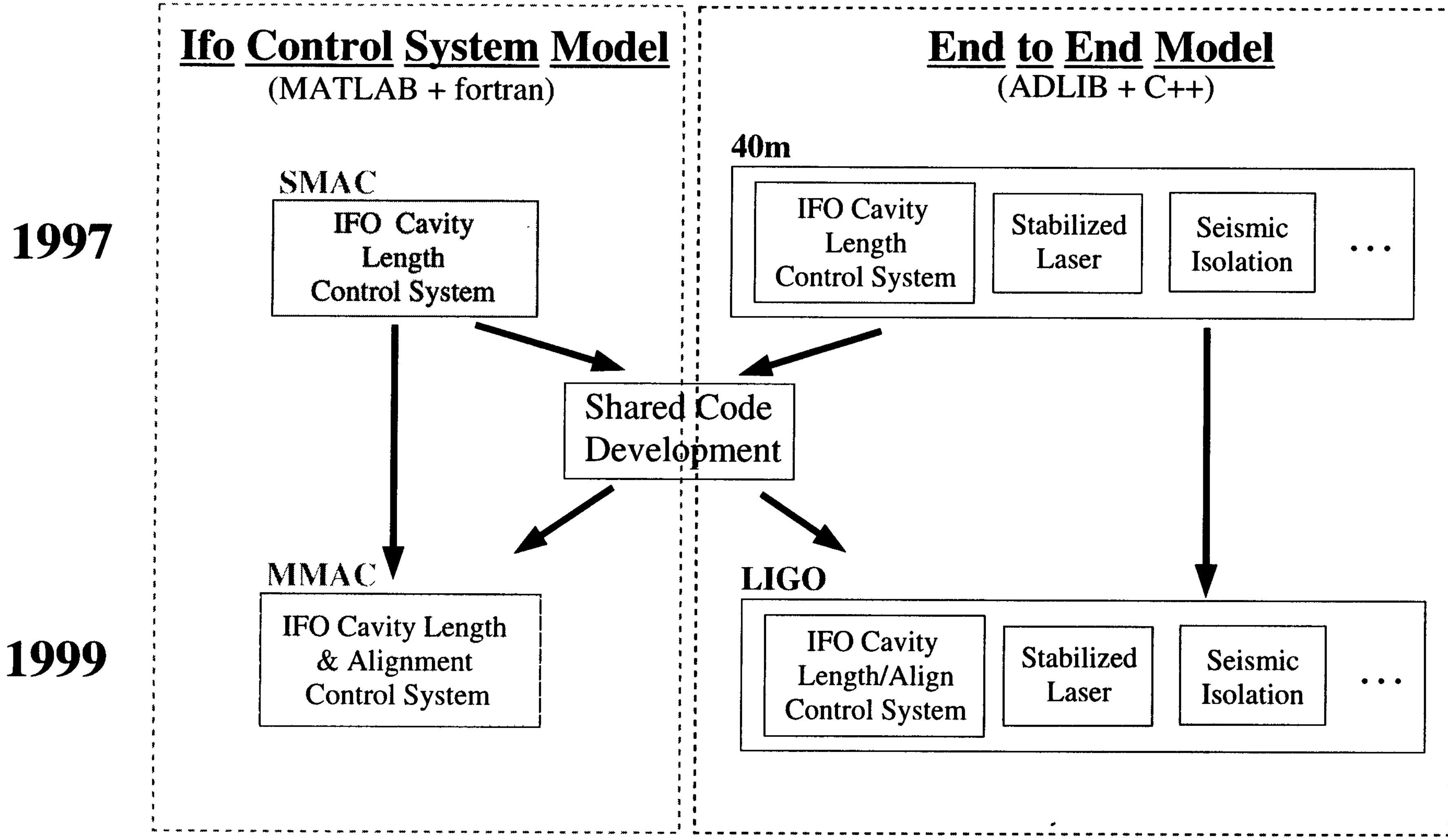
LIGO Modeling Effort

Lisa Sievers & Hiro Yamamoto

PAC on June 12&13, 1997

- Modeling activities overview
  - 1997
    - IFO Single Mode Acquisition Code (SMAC)
    - End to End model for 40m
  - 1999
    - IFO Multi Mode Acquisition Code (MMAC)
    - End to End model for LIGO
- SMAC
  - Length control design for LIGO
  - Helped to understand the locking problem of 40m
- End to End model
  - Modular / flexible / expandable
  - 40m - prototype for the LIGO End to End model
- Future plan
  - Subsystems to be included in time
  - Support for data analysis

LIGO Modeling Program



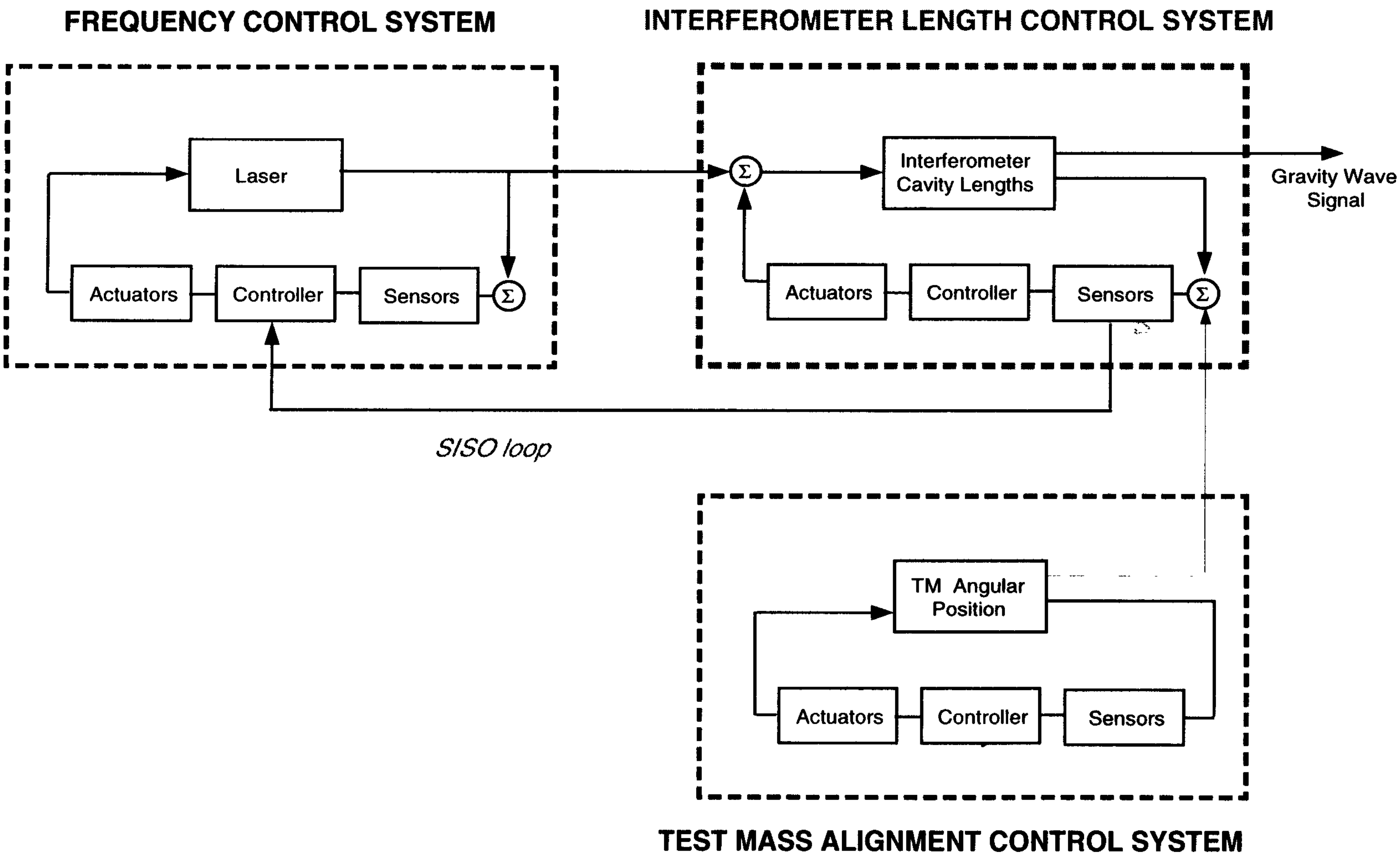
Function: Control Design Tool
and some Diagnostics

Function: Diagnostics, Pseudo Data Production
and Adanced Detector Design

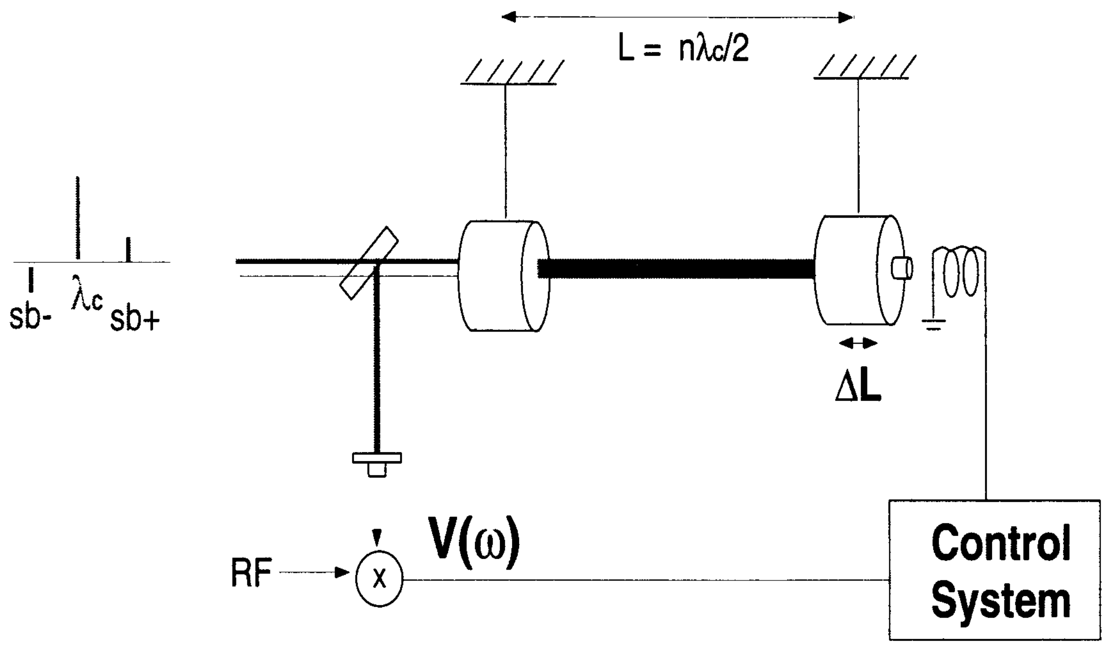
Overview of Length Control System Model (SMAC)

- Description of Interferometer Length Control System
  - Operations Mode
  - Acquisition Mode
- Modeling Framework for SMAC (Single Mode Acquisition Code)
- Insights Gained From Model
- Status of Control System Modeling Program

BLOCK DIAGRAM OF INTERFEROMETER SERVO CONTROL SYSTEMS



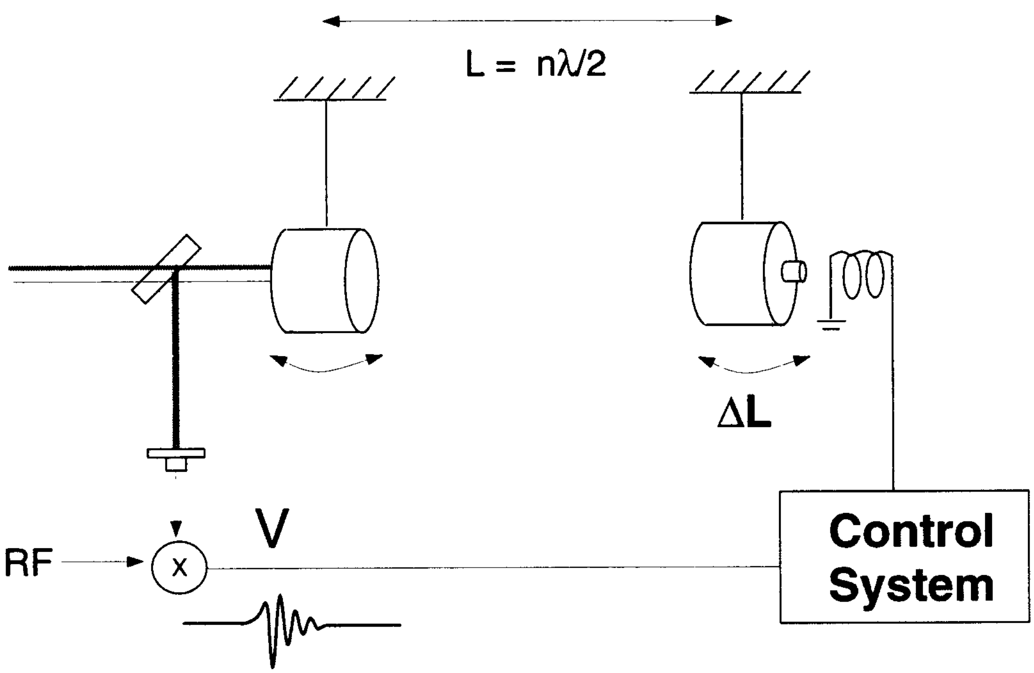
Interferometer Length Control System



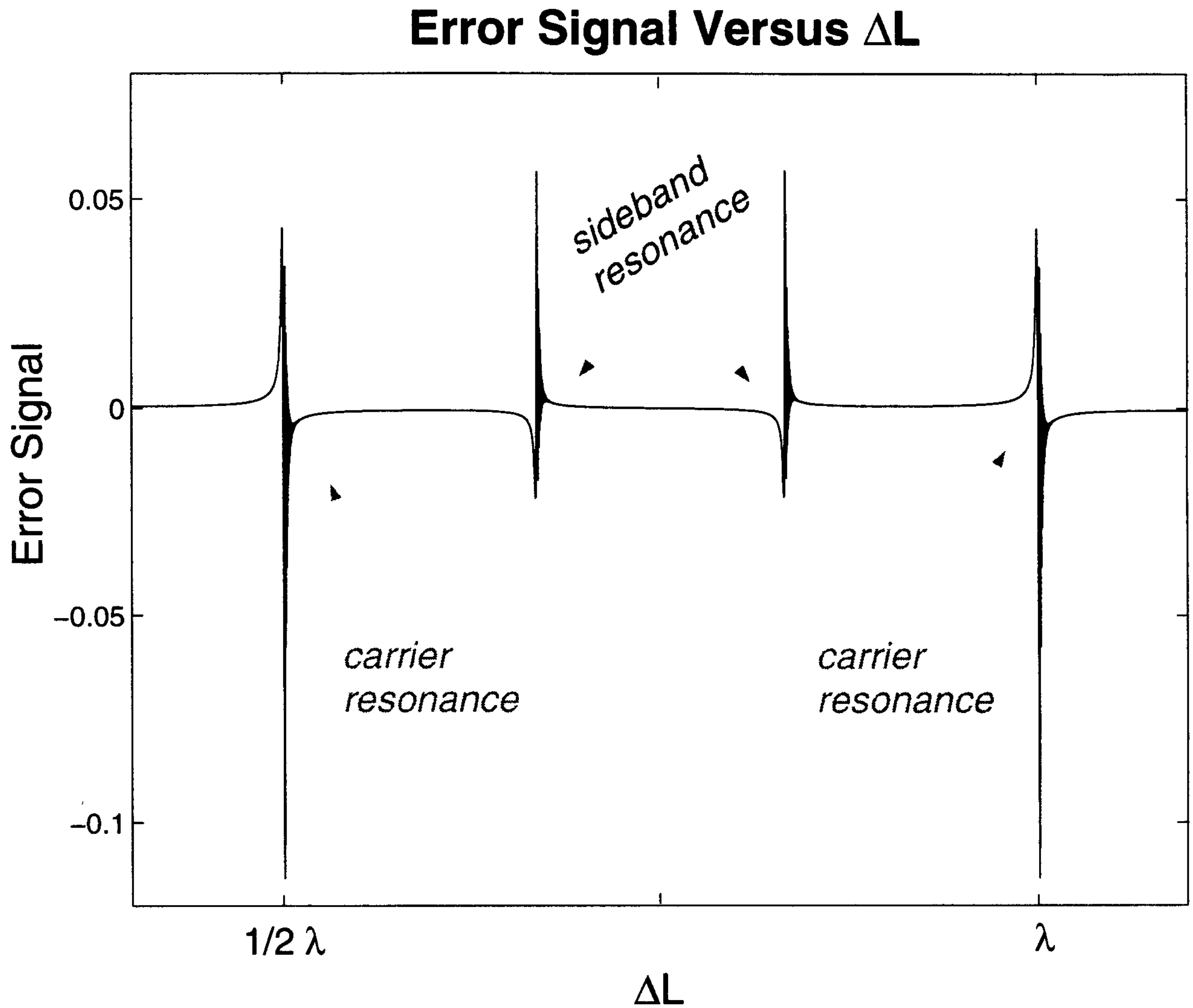
- Operations Mode
  - ›› Interferometer on resonance ==> ΔL <1 nm
  - ›› Can model as a simple linear system

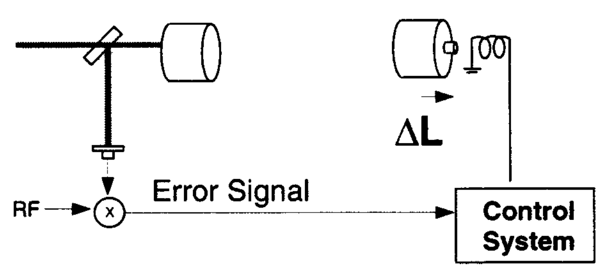
$$V(\omega) = \left(\frac{G}{2\pi j\omega + p_c}\right) \cdot \Delta L$$

Interferometer Length Control System (contd. 2)



- Acquisition Mode
  - ›› ΔL goes through many fringes
  - ›› Control signal is usable for only µsecs at a time
  - ›› Can **NOT** model as simple linear system; is a system with memory

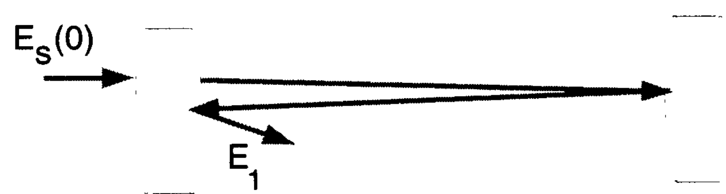

Error Signal Versus ΔL
0.05
0
−0.05
−0.1
Error Signal
sideband
resonance
carrier
resonance
carrier
resonance
1/2 λ
λ
ΔL


ΔL
RF
Error Signal
Control
System

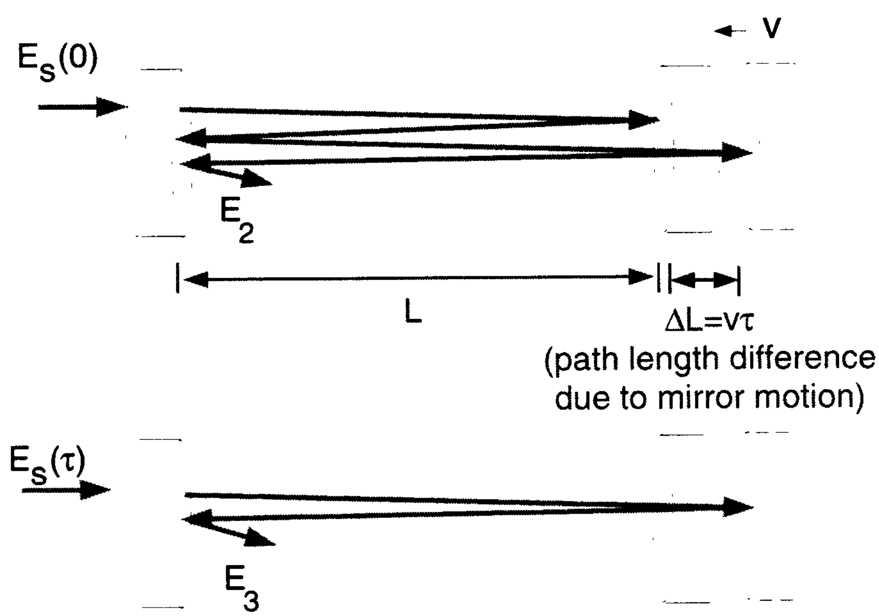
Optical Dynamics During Acquisition (memory!)

- E field in cavity at time "t" equals Σ of fields due to light entering cavity at discrete times, t, t-τ,...

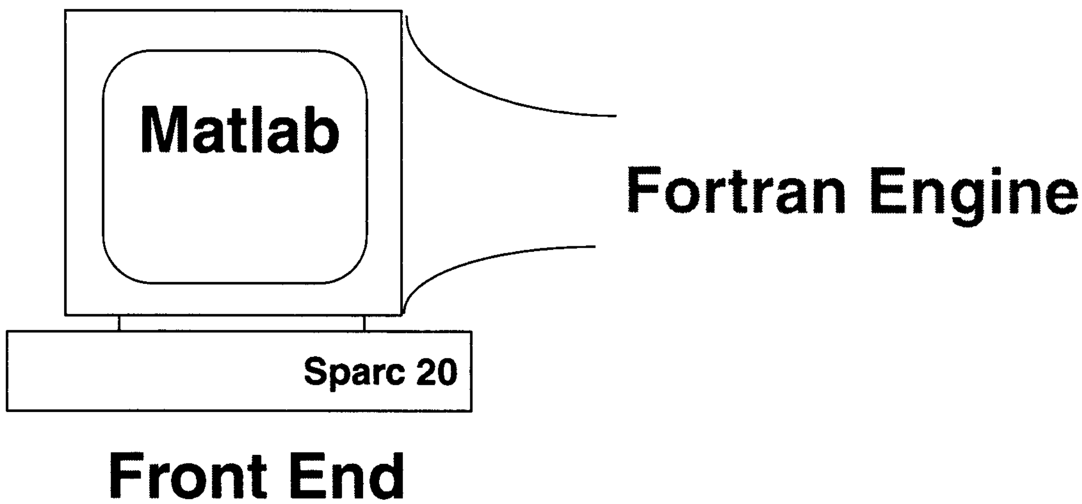
E field in cavity at τ: $E(\tau) = E_1 + tE_s$



E field in cavity at 2τ: $E(2\tau) = E_2 + E_3 + tE_s$



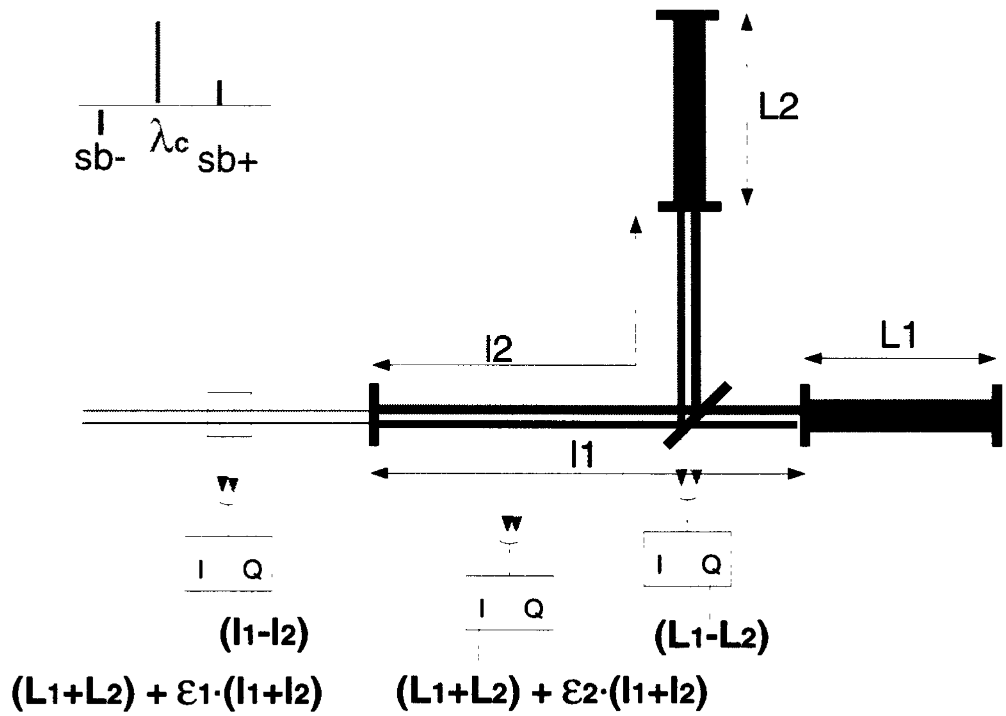
Model Framework for SMAC



- Old Worry: SPEED---thought computational intensity would demand a CRAY!!!
- LIGO Simulation Speed (SPARC 20)
  - Need to keep track of ~ 8000 past history states
  - (simulation time) / (real time) ~ 100
  - Typical real times of interest: .05 - 1 second
    - Simulation time ~ 5 - 100 seconds

Recycled Interferometer Configuration

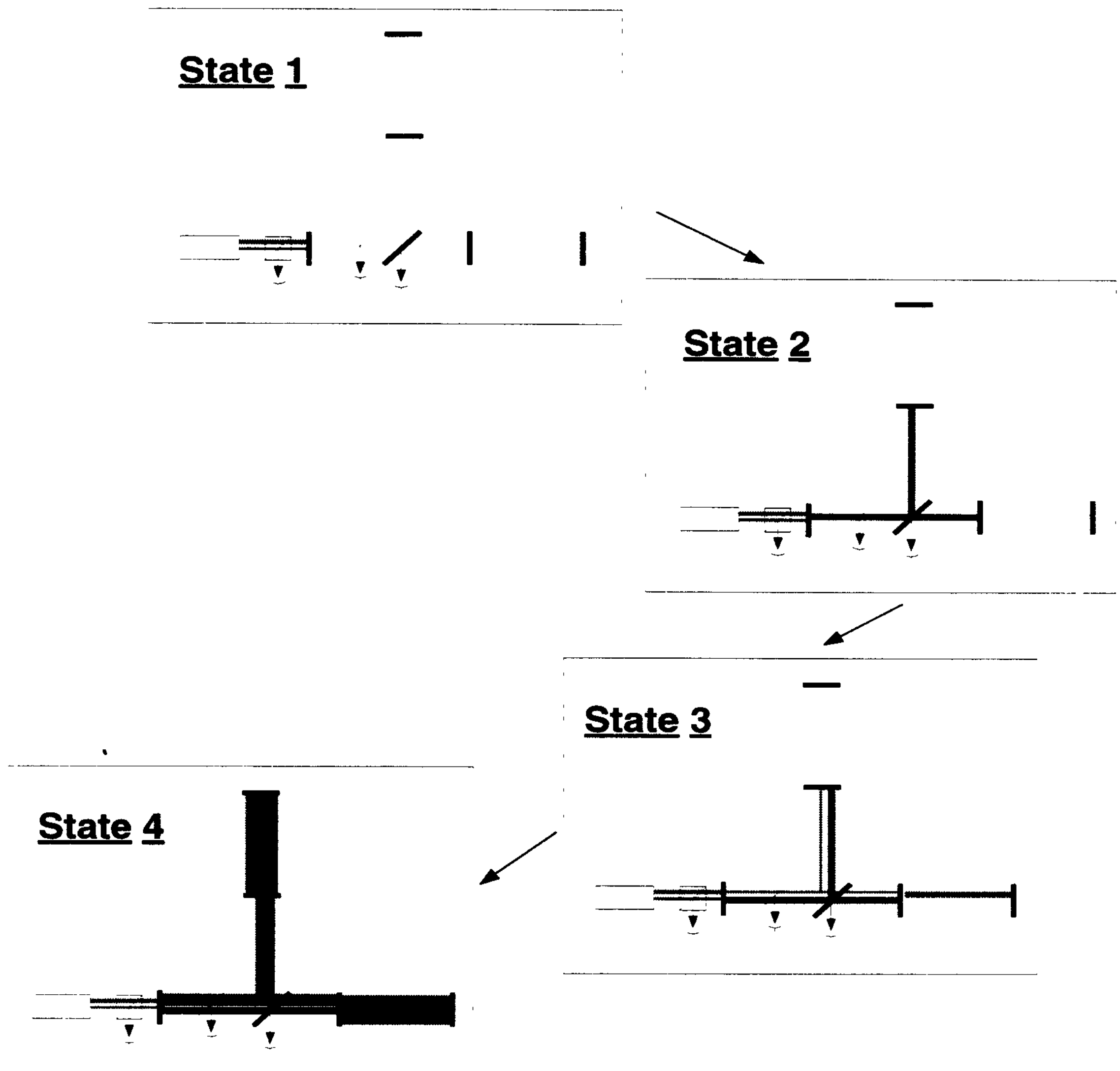
- 3 frequencies resonant in interferometer
- 4 lengths to control



	FSR	Finesse	δf	L1	l1
40 m parameters	3.9 MHz	1050	3 KHz	40 m	2 m
LIGO parameters	.0375 MHz	206	.18 KHz	4000 m	6 m

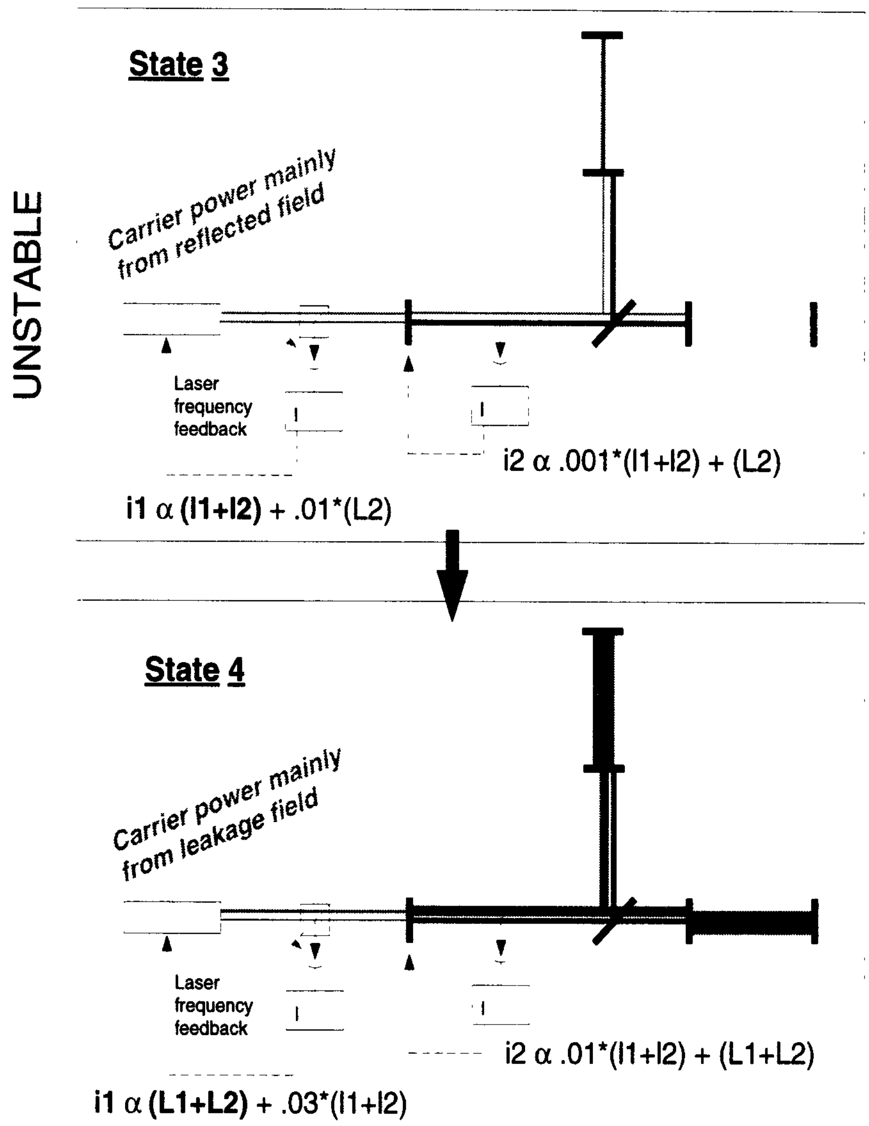
Insights for LIGO from Recycling Model

1. Locking sidebands in State 2 sets up lengths correctly for proper carrier resonance condition



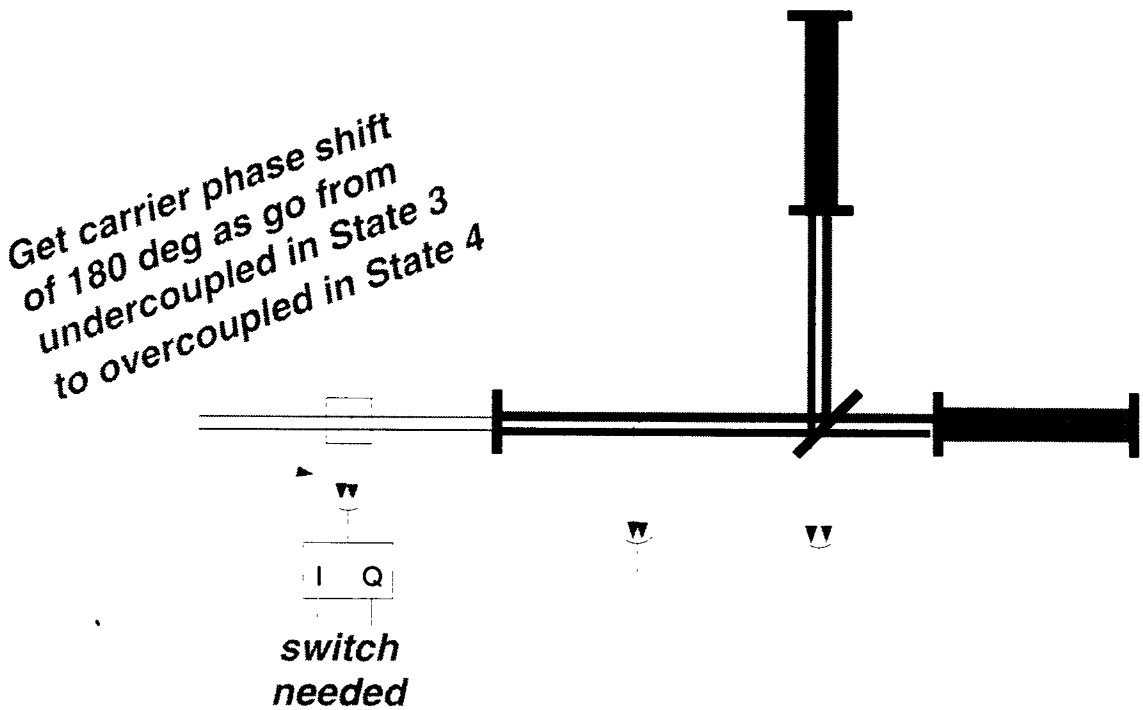
Insights for LIGO from Recycling Model (contd. 2)

2. Sensing points must be chosen so servos stable in all states (influenced initial design)



Lessons for LIGO from Recycling Model (contd. 3)

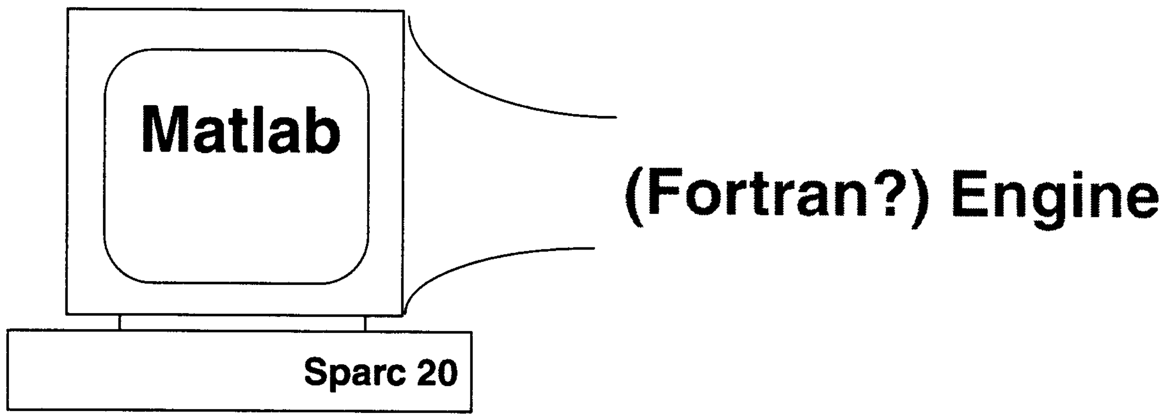
3. Michelson differential mode servo requires sign flip when it advances from State 3 to State 4 (influenced initial design)



Status of Control System Modeling Program

- Development of model for the acquisition of a LIGO interferometer is complete (SMAC code)
  - Has provided us with fundamental understanding of locking process
- Exploiting full potential of model capability is underway
  - Used as a tool for control system design, including computer control when necessary (40 m design complete)
  - Will be used as a tool for trouble-shooting experimental locking problems
  - May be used as a diagnostic tool for the interferometer
- Next phase of modeling program includes addition of higher order modes to acquisition model (MMAC)

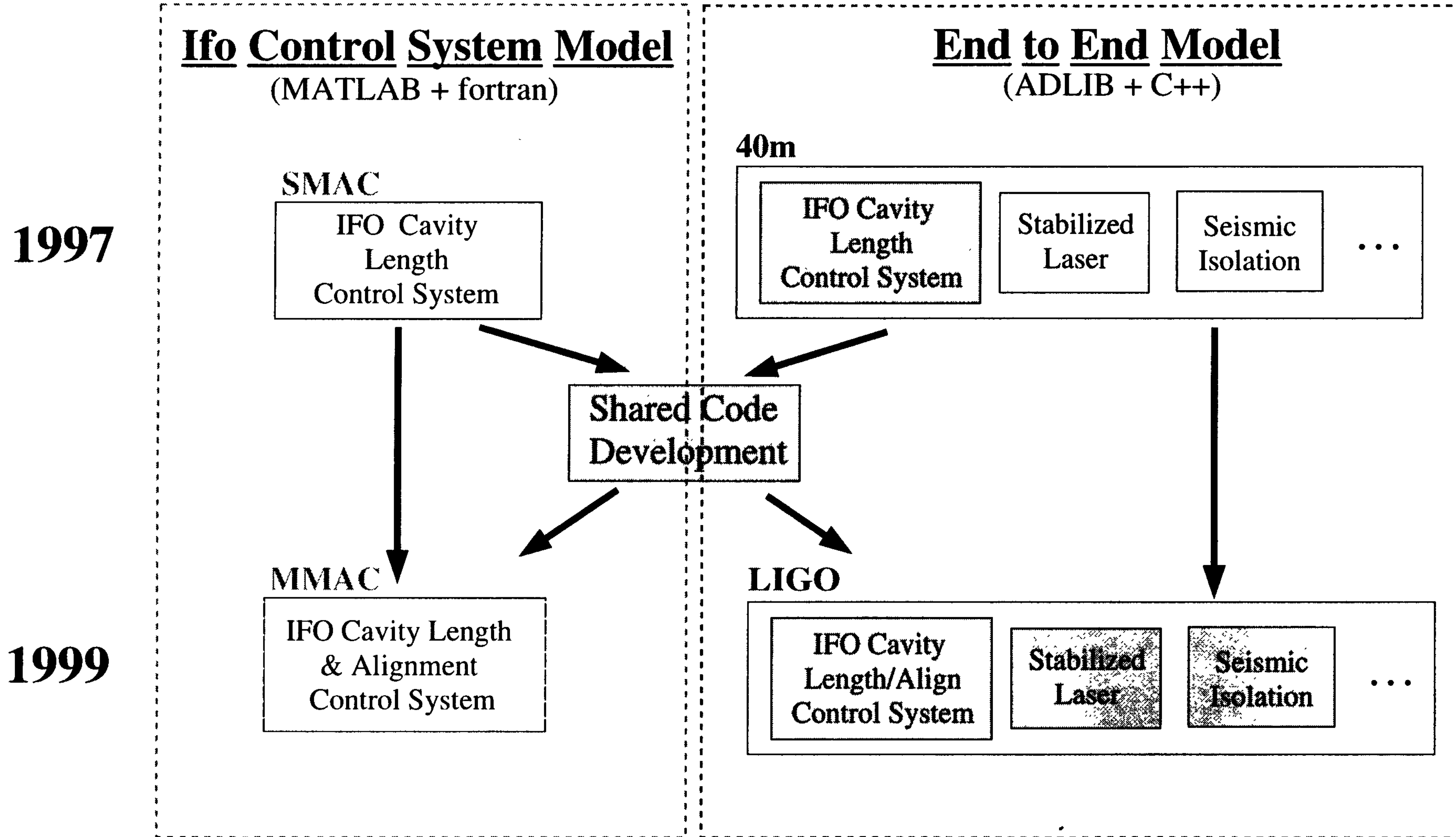
Model Framework for MMAC



Front End

- Estimate of LIGO Simulation Speed (SPARC 20)
  - (simulation time) / (real time) ~ 100 x (# modes)^2
  - Typical "real time" of interest: .05 - 1 second
    - 3 mode model: simulation time ~ .5 - 15 minutes
    - 5 mode model: simulation time ~ 2 - 40 minutes
- New/Old Worry: SPEED---computational intensity demands parallel processing?

LIGO Modeling Program



Function: Control Design Tool and some Diagnostics

Function: Diagnostics, Pseudo Data Production and Adanced Detector Design

End to End model

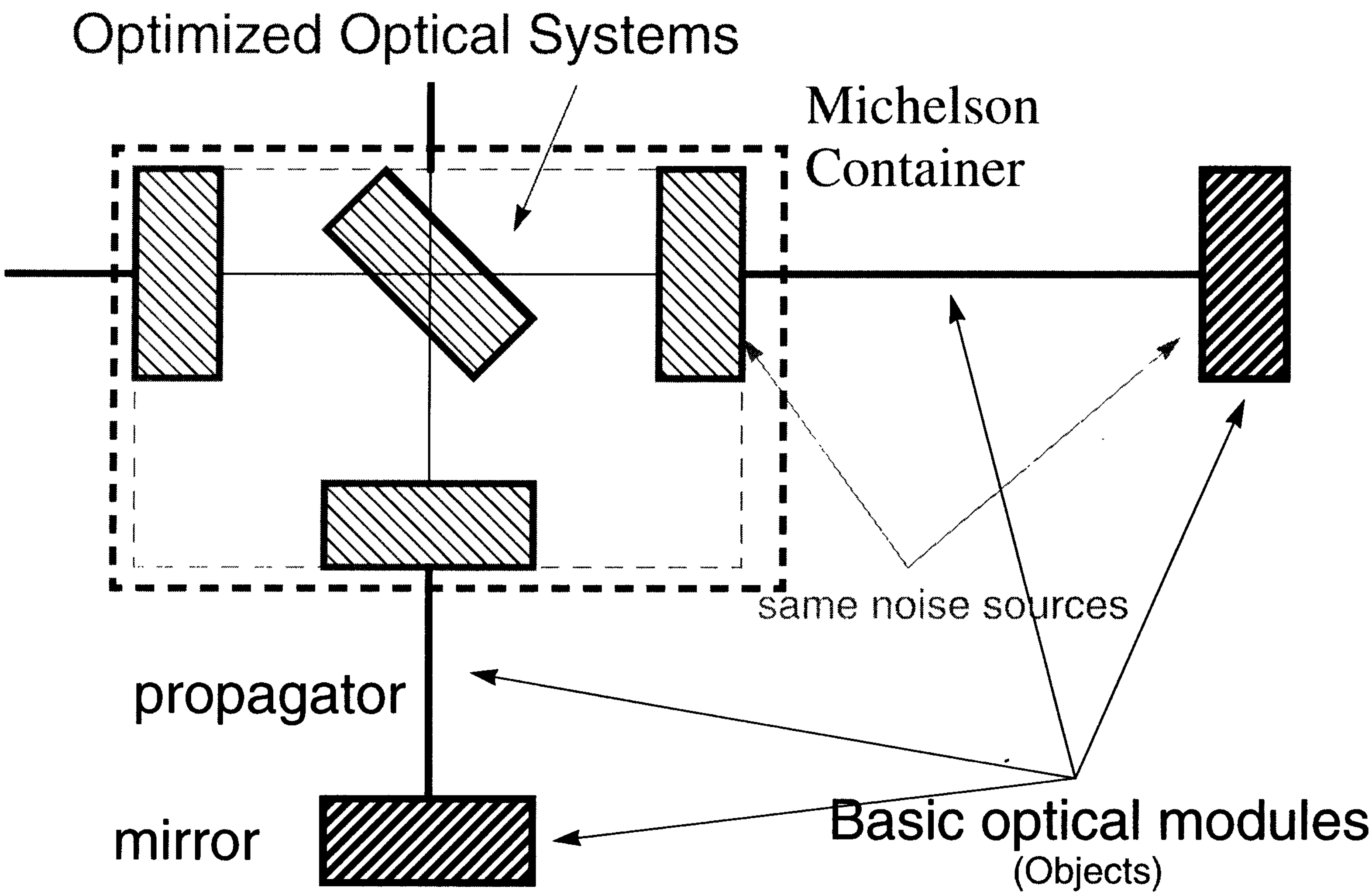
- Purpose
  - ›› LIGO software/hardware diagnostics
  - ›› Generate pseudo-data for data analysis study
  - ›› Advanced R&D technology design study
- Framework
  - ›› ADLIB (AdLib, the Digital Instrument Builder) by M. Evans
  - ›› Time domain model written in C++
    - – Object oriented modular design
    - – Speed optimization best suited for LIGO simulation
  - ›› Digital Filter
  - ›› Modular and Expandable
    - – both low level and high level
- Status
  - ›› 40 m model as prototype
    - – Existing detector
    - – Building block validation
    - – Reliability test
  - ›› Under construction
    - – missing many things
    - – no good interface (text editor and gnuplot)

ADLIB
overview

- ADLIB
  - ›› Framework for the time domain simulation
    - written in C++
    - object oriented
  - ›› high level layer
    - easy prototyping
    - no C++/C/Fortran coding needed
    - dynamic module binding
    - optimized for speed and memory usage
- Simulation
  - ›› Setup is defined by combining modules
    - Basic optic modules (mirror, beam splitter, etc.)
    - Digital Filter
    - Container (assembled modules)
  - ›› If some part of the simulation is slow, replace a container by a new optimized module
    - Modification is possible without major code restructuring

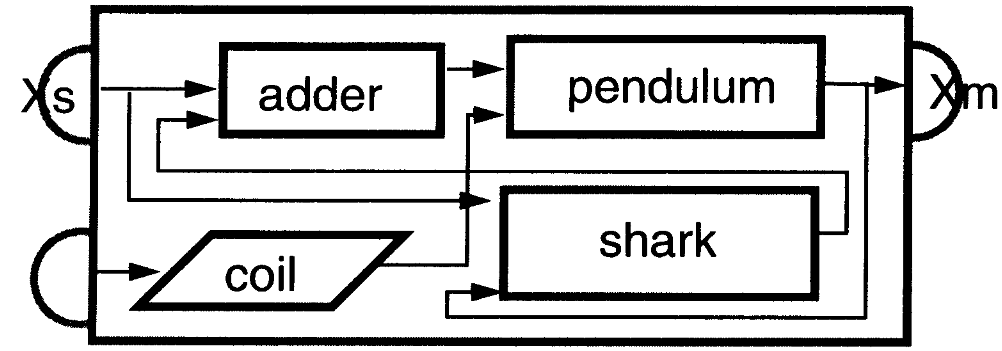
ADLIB Optics

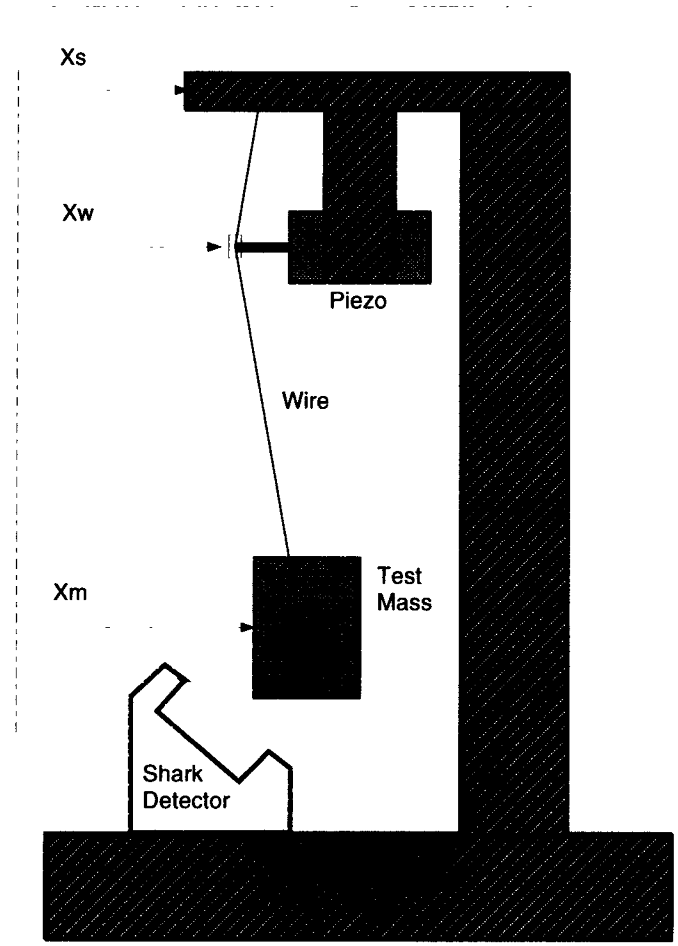
example of modularity



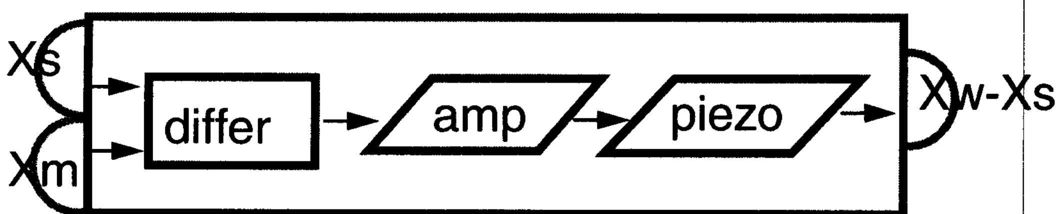
Example
Suspension system

Suspension

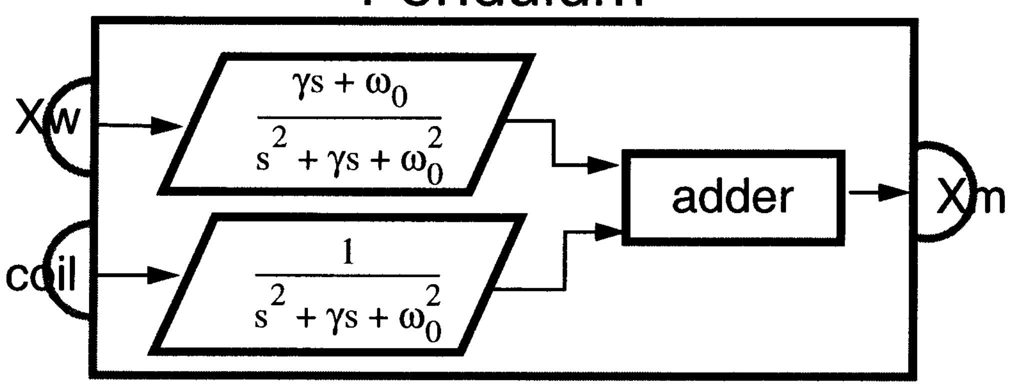




Shark



Pendulum



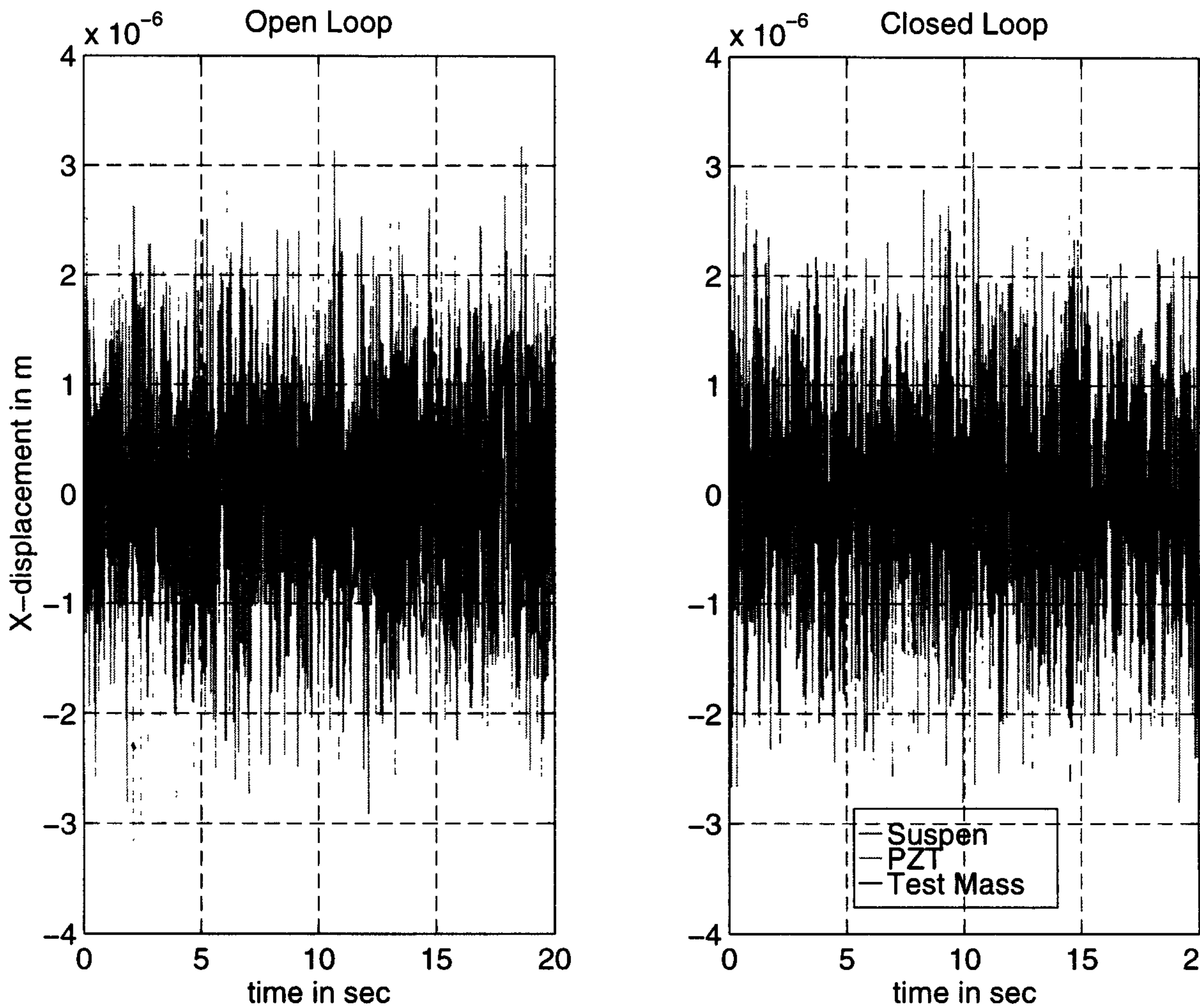
Description Files
pendulum.box

```
Submodules
%Module Type   Reference Name  Build File Name
filter         xsprt          pend_x.mod
filter         force          pend_f.mod
madder         adderA
End

Connections
% module input -> submodule input
this 0 -> xsprt 0
this 1 -> force 0
% submodule outputs -> submodule inputs
xsprt 0 -> adderA 0
force 0 -> adderA 2
% submodule output -> module output
adderA 0 -> this 0
End
```

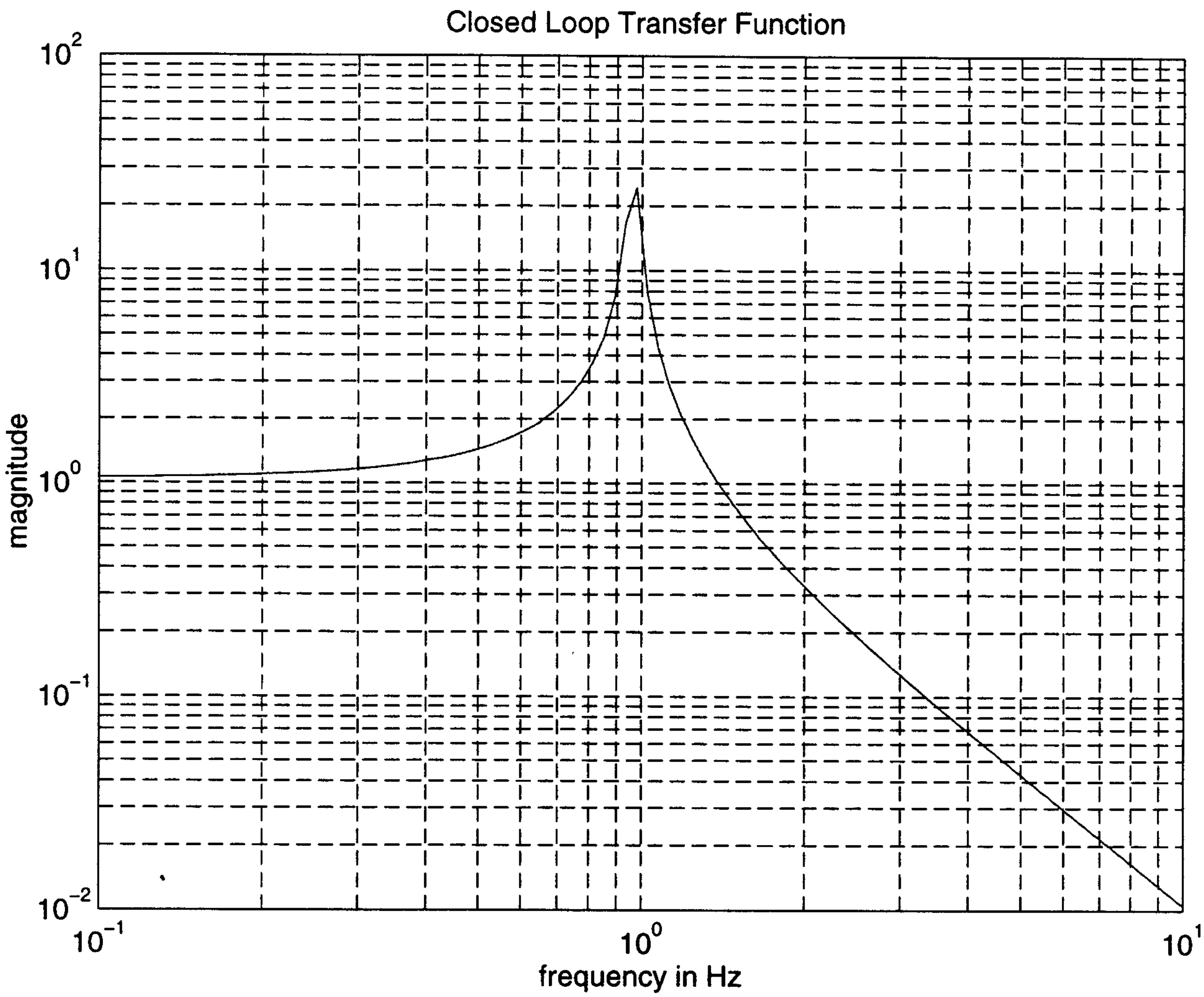
Test mass motion

open vs closed loop



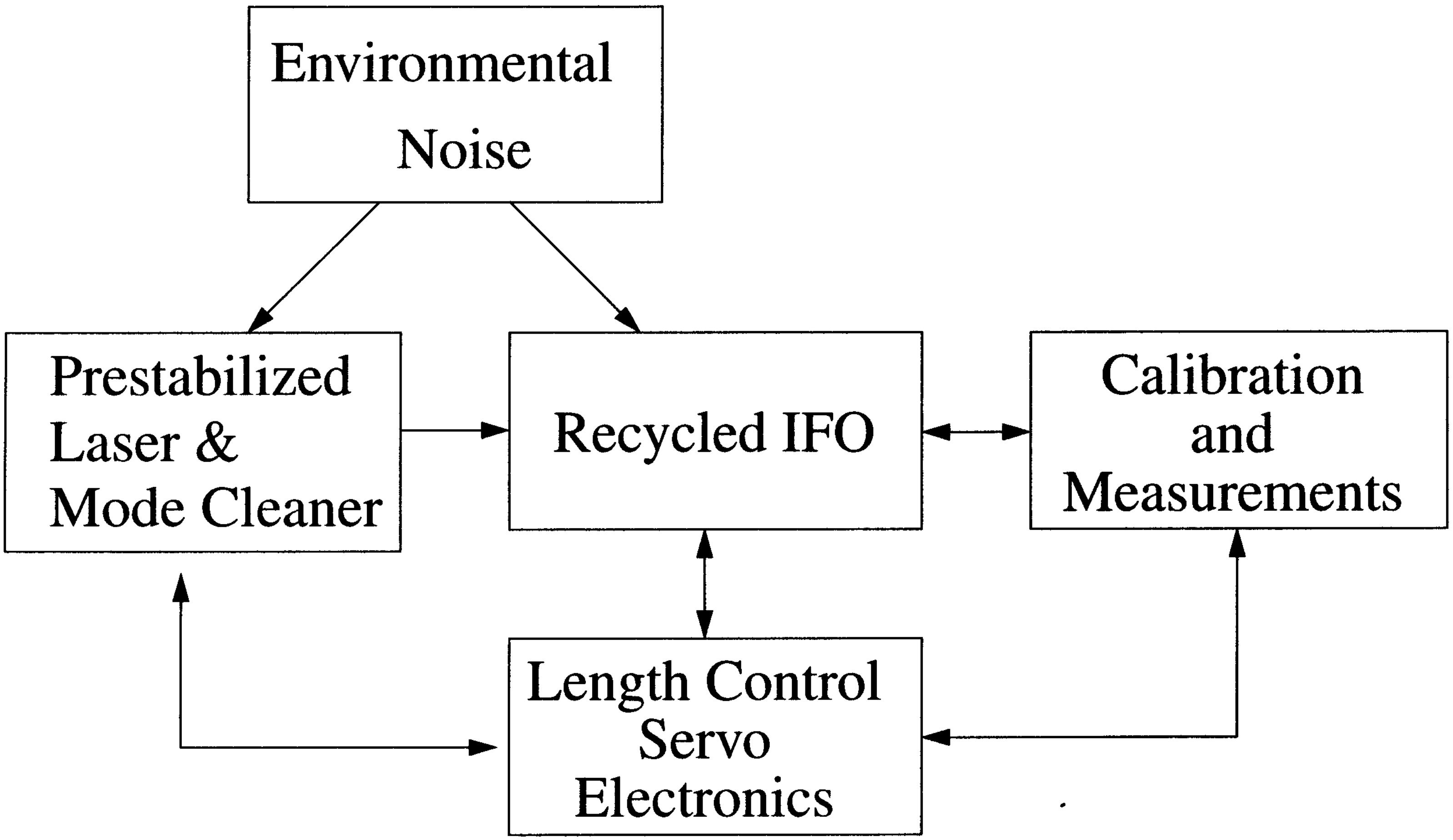
Transfer Function

closed loop



40m prototype
elements of end to end model

•



End to End model
issue - 1

- Refine components
- Validation using 40m lab
  - proposal being prepared
  - understand the confidence level
- Adoption of small signal model as Compound Optics system
  - small signal model is fast and reliable
  - Use frequency domain model in the time domain via digital filter
- Inclusion of alignment degree of freedom
- Graphical User Interface
  - Easy construction of modules
  - Integrated data visualization
- Merger of MMAC and LIGO End to End model

End to End model
issue - 2

- What subsystems to be included for detector support
  - ›› Core optics
    - – IFO with alignment & control
    - – Imperfection of mirrors
  - ›› Alignment and Length control
  - ›› Prestabilized laser, input optics/mode cleaner, suspension ...
- What are needed for data analysis support
  - ›› Which subsystems
  - ›› Level of sophistication
  - ›› What should go to Frame MC block
  - ›› Duration of simulation
- Prioritization & order of completion
- What are to be done by the time when LIGO hardware is ready to turn on.

PAC Meeting, MIT, Friday June 13th, 1997

GRAVITATIONAL RADIATION ANALYSIS
AND SIMULATION PACKAGE (= GRASP)

- Problem: Most data analysis techniques/ideas developed theoretically *but not studied on real GW-detector data.*
- Solution: Use 45 hours of data from November 1994, and forthcoming 40-meter prototype data.
- Purpose: Test-bed for prototyping data analysis techniques.
  - Implement/document "benchmark" algorithms (example: Wiener matched filtering for binary inspiral detection)
  - Comparison of different algorithms (example: Wigner-Ville vs. Wiener)
  - Answer specific technical questions (example: effects of quantization error on binary inspiral search)
  - Provide means for others (including those "outside" the LIGO project) to see & experiment with real data (example: Thorne's group)
  - Popularize/Illustrate the FRAME data format.
- Form: A portable function library (Posix/ANSI C) with extensive documentation, and example programs to illustrate the different functions. Works on Sun, Dec, HP, Linux, SP2, Paragon. Only requirements are either public domain (i.e. xmgr) or inexpensive (i.e. *Numerical Recipes*).

Some quotes:

- Jon Bentley, *Writing efficient programs*: "Prototype, prototype, prototype!
- Fredrick C. Brooks, *The mythical man-month*, "Plan to throw one away; you will, anyhow."
- Franklin Roosevelt, "It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something."

HOW IS GRASP ORGANIZED?

The organization of GRASP is hierarchical, closely paralleled by the manual:

- **Introduction:** Purpose, quick start, hardware/software requirements, installation, file structure, conventions.
- **40-meter data:** Data format, reading routines. Examples include:
  - reading blocks
  - finding locked sections
  - animation of data/power-spectra
  - printing swept-sine calibration curves
  - animated & calibrated power spectra
  - sonogram diagnostics
- **Binary inspiral:** 2nd PN-order chirp generation, chirp-filter production, Wiener filtering, orthonormalization of filters, convolution of chirps with detector response function, injection of chirps in time/frequency domain, vetoing techniques, setting up template grid in parameter space, optimal filtering through a single template, optimal filtering through template grid. Examples include:
  - plotting chirp
  - constructing filter set
  - optimal filtering through a single (pair of) filters
  - area of parameter space
  - constructing grid of templates
  - plotting template grid
  - optimal filtering through template bank covering $m_1 \rightarrow m_2$ (MPI).
- **Stochastic BG:** Detector site location/orientation, overlap reduction function, simulated detector noise production in time domain (arbitrary whitening/dewhitening), simulated correlated stochastic background production, optimal correlated filtering, statistical analysis for stochastic background. Examples include
  - plotting overlap reduction function for any detector pair
  - simulated detector noise & SB at two sites
  - plotting optimal filter for SB detection

- determining (theoretically-expected SNR) after integration time T
- predicting integration time necessary to observe background of given intensity Ω
- Monte-Carlo simulation of analysis pipeline

- **General-purpose:** time-averaged power spectra, histogram binning, robust outlier detection, graphing routines (using `xmgr`), audio/sound routines, multitaper window function, multitaper spectra, spectral line identification, spectral line removal, interface to frame library. Examples include:
  - translator from November 1994 40-meter format to FRAME format
  - removing "spectral lines" from Willamette river data
  - identifying/removing spectral lines from "raw" 40-meter output
  - tracking line harmonic/violin mode frequency, phase, amplitude

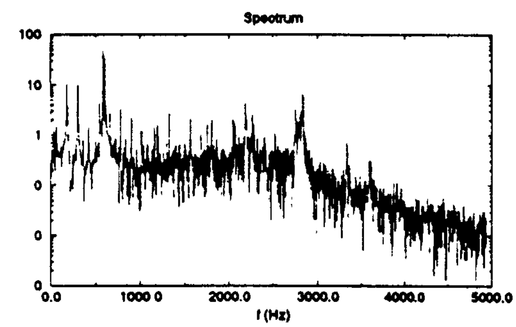
All examples work on *either* FRAME format data or on November 1994 data (though the latter is planned to become obsolete).

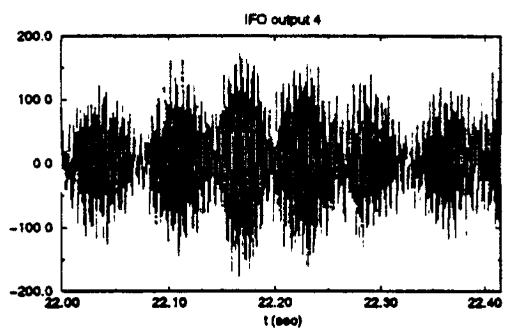
This talk: show some examples from GRASP, lessons learned; discuss future work & questions that need further investigation.

EXAMPLE - `animate` program

This example displays a window showing the raw IFO output in real time and its spectrum in real time.

```
animate | xmgr -pipe
```





One of the interesting things that I found was that after the instrument comes into lock, the output is *zero* (up to DC offsets). The explanation: the SR output amps are saturated when the instrument is out of lock. Because they are AC-coupled, the IFO channel is zero. After coming into lock (unless someone presses the reset button!) the amplifiers take from 5 to 30 seconds to come out of saturation which provides a non-zero IFO output.

CALIBRATION

The calibration of the instrument is stored in swept-sine calibration files (801 line ascii files containing 3 columns: frequency, real, imaginary). GRASP includes a function which returns $R(f)$, defined by

$$\widetilde{\Delta l} = R(f) \times \widetilde{C_{\rm IFO}} \qquad \text{with} \quad R(f) = \frac{Q \times \mathrm{ADC}}{-4\pi^2 f^2 S^*(f)}.$$

Here "tilde" denotes Fourier transform and $C_{\rm IFO}$ is the IFO differential-mode output, channel 0.

Description	Name	Value	Units
Gravity-wave signal (IFO_DMRO)	$C_{\rm IFO}$	varies	ADC counts
A→D converter sensitivity	ADC	10/2048	$\mathrm{V_{IFO}\ (ADC\ counts)^{-1}}$
Swept sine calibration	S(f)	from file	$\mathrm{V_{IFO}\ (V_{coil})^{-1}}$
Calibration constant	Q	1.428×10^{-4}	$\mathrm{meter\ Hz^2\ (V_{coil})^{-1}}$

Table 1: Quantities entering into normalization of the IFO output.

$Q = \frac{\sqrt{9.35\ \mathrm{Hz}}}{k} = 1.428 \times 10^{-4} \frac{\mathrm{meter\ Hz^2}}{\mathrm{V_{coil}}}$, with $k = 21399 \frac{\mathrm{V_{coil}}}{\mathrm{meter\ Hz^{3/2}}}$.

One of the interesting things I found was that there was no documentation showing the phase conventions. In other words, did imaginary part positive mean that the phase was leading or lagging? Eventually Bob and I did a simple experiment with an RC circuit to establish the phase conventions.

EXAMPLE - `calibrate` program

This program produces a (calibrated!) time-averaged power spectrum, making use of the response function $R(f)$.

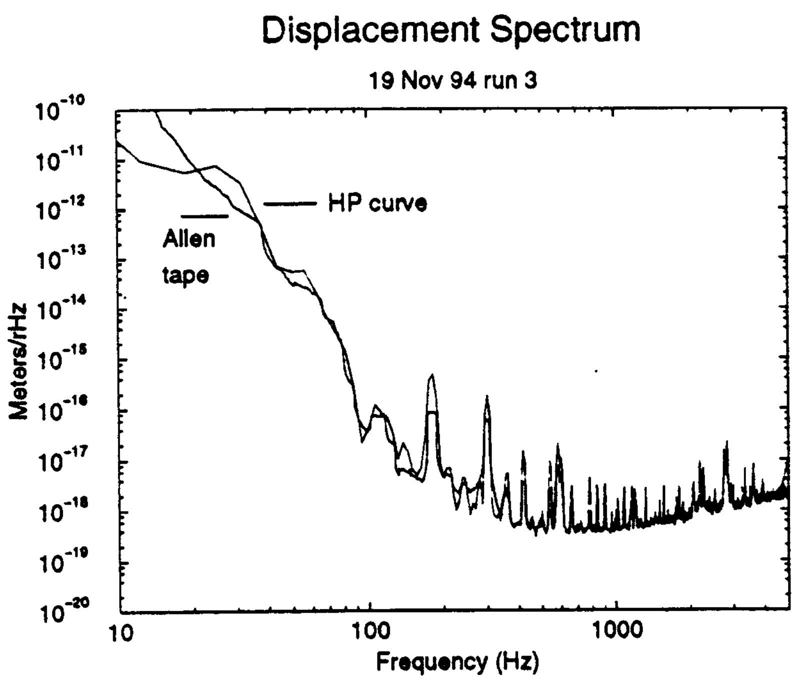
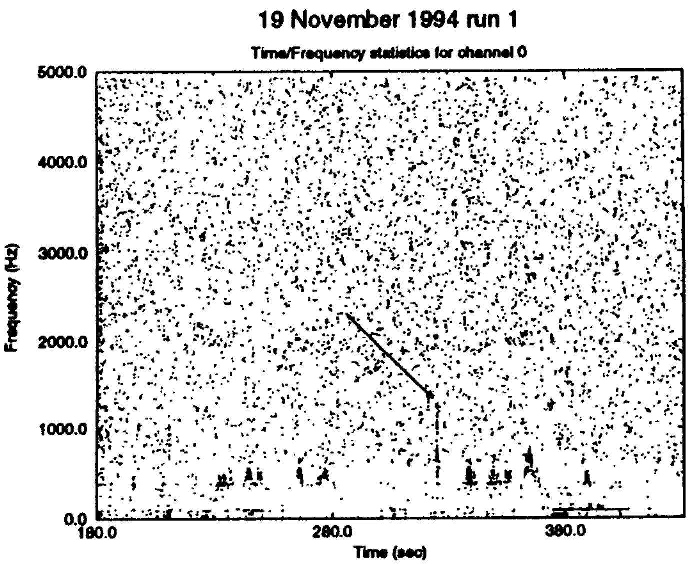


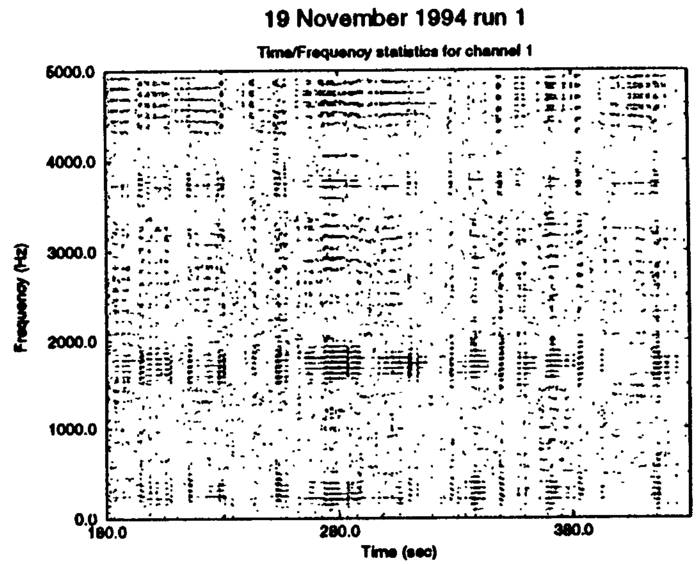
Figure 1: An example of a power spectrum curve produced with `power_spectrum`. The spectrum produced off a data tape (with 100 point smoothing) is compared to that produced by the HP spectrum analyzer in the lab.

This was the first time that anyone had used the data on tape to produce a calibrated power spectrum – prior to this the only calibrated spectra had come off the HP signal analyzer in the 40-meter lab.

Plans for 40 Meter Data Analysis

On-line Analysis: *(Time-Frequency Method)*

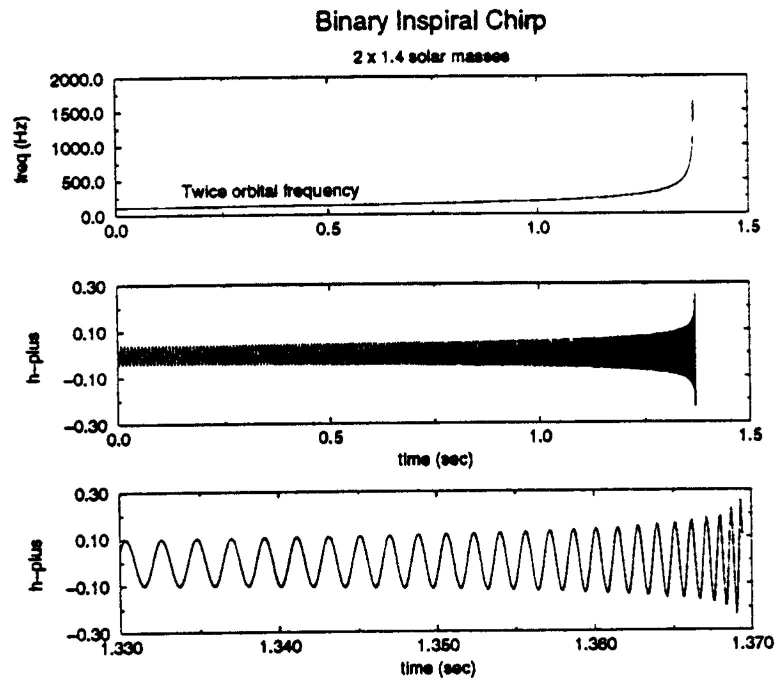




- **Exponentially weighted running power spectrum**
- **Gravitational wave channel on left**
- **Coincident magnetometer channel on right**
- **Provides useful detector diagnostics**
- **Allows non-Gaussian noise characterization**

EXAMPLE - `filters` program

This is a program which was written in collaboration with Alan Wiseman. It produces properly-normalized binary inspiral chirps.



- Post-Newtonian corrections (optionally) included up to second order in amplitude and/or phase.
- Warns user of a variety of different error conditions.
- Automatically terminates chirp when post-Newtonian approximation or other assumptions no longer hold.

EXAMPLE - optimal program

This is a program which filters IFO output through a single binary inspiral template – in this case choosen to be 2×1.4 solar mass objects.

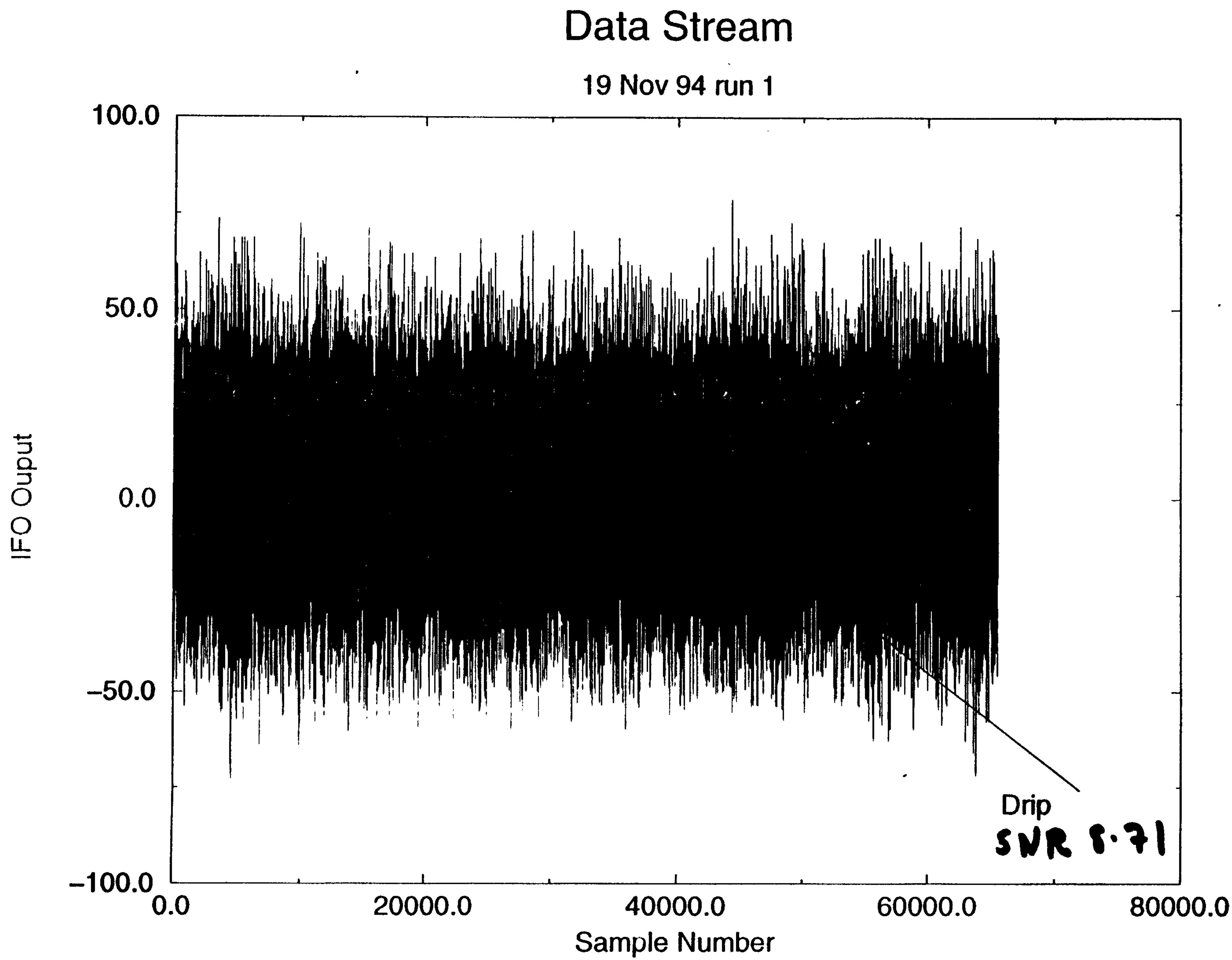
```
...
max snr: 3.11 offset: 23623 data start: 180.00 sec. variance: 0.94044
max snr: 2.91 offset: 3311 data start: 185.17 sec. variance: 0.84484
...
max snr: 2.53 offset: 19041 data start: 309.26 sec. variance: 0.70333
max snr: 2.98 offset: 35711 data start: 314.43 sec. variance: 0.67523
max SNR: 8.71 (offset 42109) variance 0.805030
   If impulsive event, offset 55624 or time 325.23
   If inspiral, template start offset 42109 (time 323.86) coalescence time 325.23
   Normalization: S/N=1 at 116.75 kpc                                                  #1
   Linear combination of max SNR: 0.9315 x phase_0 + 0.3638 x phase_pi/2
   Less than 1% probability that this is a chirp (p=0.000000).
   Distribution: s= 23, N>3s= 12 (expect 176), N>5s= 0 (expect 0)
   Distribution does not appear to have outliers...
max snr: 2.51 offset: 31183 data start: 324.77 sec. variance: 0.63028
max snr: 2.56 offset: 49909 data start: 329.94 sec. variance: 0.66853
...
max snr: 2.82 offset: 35080 data start: 3002.03 sec. variance: 0.77306
max snr: 2.61 offset: 33141 data start: 3007.20 sec. variance: 0.74268
max SNR: 89.75 (offset 16678) variance 82.547005
   If impulsive event, offset 30193 or time 3015.43
   If inspiral, template start offset 16678 (time 3014.06) coalescence time 3015.43
   Normalization: S/N=1 at 123.49 kpc
   Linear combination of max SNR: -0.3955 x phase_0 + 0.9185 x phase_pi/2              #2
   Less than 1% probability that this is a chirp (p=0.000000).
   Distribution: s= 29, N>3s= 157 (expect 176), N>5s= 30 (expect 0)
   Distribution has outliers! Reject
max snr: 3.24 offset: 22412 data start: 3017.54 sec. variance: 0.99474
max snr: 2.73 offset: 37777 data start: 3022.71 sec. variance: 0.75325
...
max snr: 2.80 offset: 5893 data start: 4140.89 sec. variance: 0.73240
max snr: 2.75 offset: 46932 data start: 4146.06 sec. variance: 0.69654
max SNR: 6.08 (offset 30002) variance 0.883380
   If impulsive event, offset 43517 or time 4155.64
   If inspiral, template start offset 30002 (time 4154.27) coalescence time 4155.64
   Normalization: S/N=1 at 113.04 kpc                                                  #3
   Linear combination of max SNR: -0.4773 x phase_0 + 0.8787 x phase_pi/2
   POSSIBLE CHIRP!  with > 1% probability (p=0.024142).
   Distribution: s= 31, N>3s= 399 (expect 176), N>5s= 53 (expect 0)
   Distribution has outliers! Reject
max snr: 2.77 offset: 15985 data start: 4156.40 sec. variance: 0.72095
max snr: 2.69 offset: 47338 data start: 4161.57 sec. variance: 0.69708
...
```

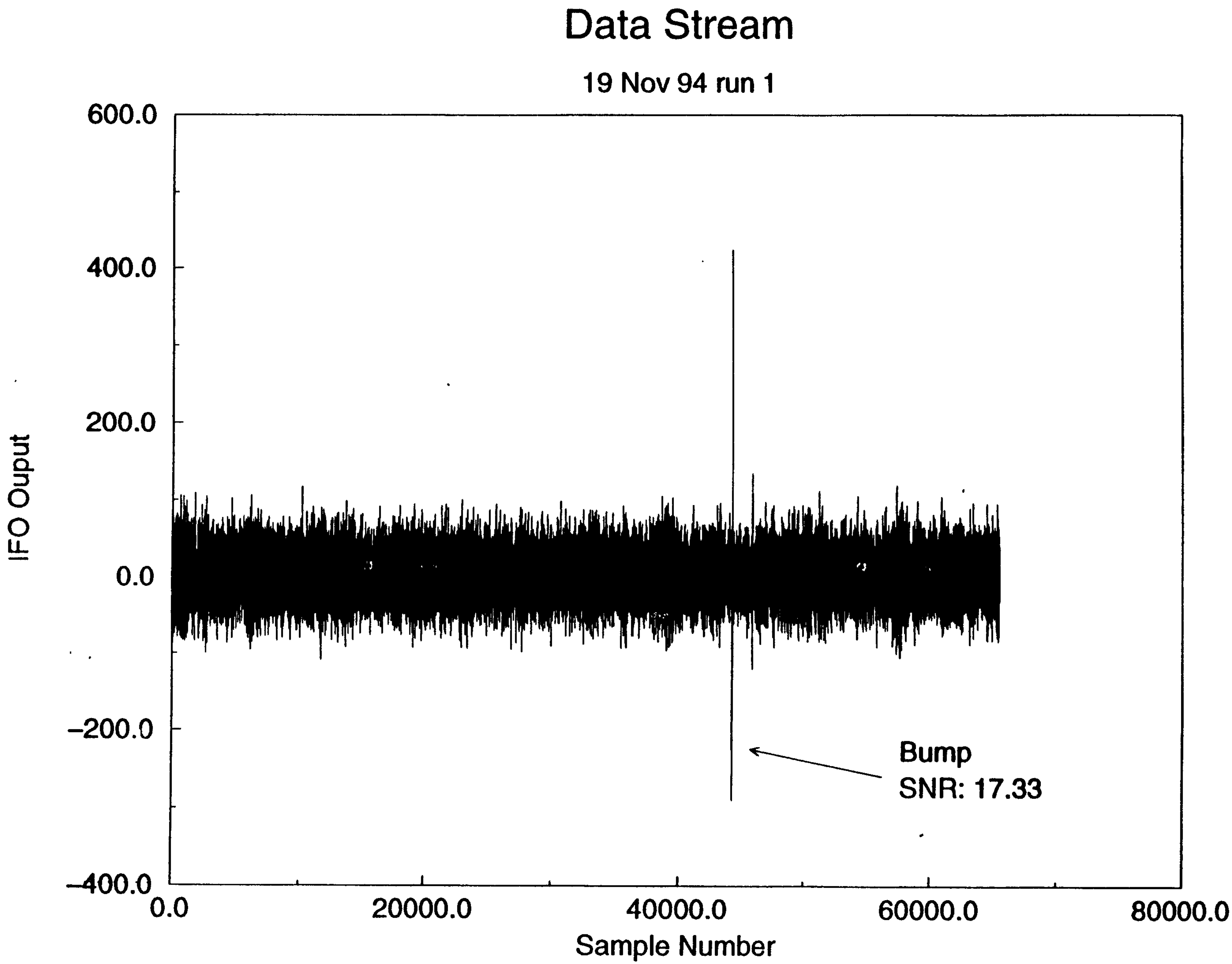
The events were rejected because:

Event 1: Failed the frequency-distribution test.

Event 2: Failed the outlier test (and the frequency distribution test).

Event 3: Failed the outlier test (but passed outlier test, barely!)


Data Stream
19 Nov 94 run 1
100.0
50.0
0.0
−50.0
−100.0
IFO Ouput
0.0
20000.0
40000.0
60000.0
80000.0
Sample Number
Drip
SNR 8.71


Data Stream
19 Nov 94 run 1
600.0
400.0
200.0
0.0
−200.0
−400.0
IFO Ouput
0.0
20000.0
40000.0
60000.0
80000.0
Sample Number
Bump
SNR: 17.33

Chirp Injection (in time or freq domain)

```
invMpc_inject=100.0;    /* To inject a signal at 10 kpc, set this to 100.0 */
time_inject(1.0,0.0,12345,invMpc_inject,chirp0,chirp90,data,response,output0,npoint);
```

This produces the following output:

```
...
max  SNR: 9.96 (offset 12345) variance 0.872624
   If impulsive event, offset 25860 or time 187.79
   If inspiral, template start offset 12345 (time 186.42) coalescence time 187.79
   Normalization: S/N=1 at 152.17 kpc
   Linear combination of max SNR: 0.9995 x phase_0 + -0.0304 x phase_pi/2
   POSSIBLE CHIRP!  with > 1% probability (p=0.421294).
   Distribution: s= 23, N>3s= 12 (expect 176), N>5s= 0 (expect 0)
   Distribution does not appear to have outliers...

max SNR: 12.84 (offset 12345) variance 0.834527
   If impulsive event, offset 25860 or time 192.96
   If inspiral, template start offset 12345 (time 191.59) coalescence time 192.96
   Normalization: S/N=1 at 132.47 kpc
   Linear combination of max SNR: 0.9953 x phase_0 + 0.0973 x phase_pi/2
   POSSIBLE CHIRP!  with > 1% probability (p=0.949737).
   Distribution: s= 22, N>3s= 28 (expect 176), N>5s= 0 (expect 0)
   Distribution does not appear to have outliers...

max SNR: 14.86 (offset 12345) variance 0.801640
   If impulsive event, offset 25860 or time 198.13
   If inspiral, template start offset 12345 (time 196.76) coalescence time 198.13
   Normalization: S/N=1 at 127.90 kpc
   Linear combination of max SNR: 0.9993 x phase_0 + -0.0372 x phase_pi/2
   POSSIBLE CHIRP!  with > 1% probability (p=0.999236).
   Distribution: s= 22, N>3s= 35 (expect 176), N>5s= 0 (expect 0)
   Distribution does not appear to have outliers...
...
```

Conclusion: we can detect chirps in the GW signal, and reject spurious events.

Plans for 40 Meter Data Analysis

Gravitational Radiation Analysis & Simulation Package (GRASP):

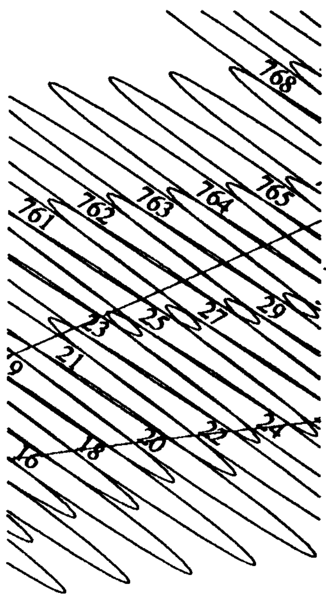
Binary Inspiral Template Spacing

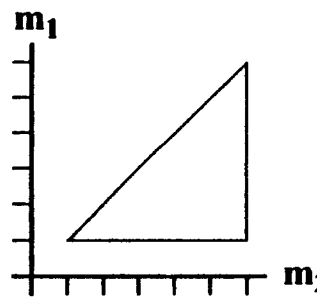
$$\tau_0 = \frac{5}{256} \cdot \left(\frac{G \cdot M}{c^3}\right)^{-5/3} \cdot \eta^{-1} \cdot (\pi \cdot f_o)^{-8/3}$$

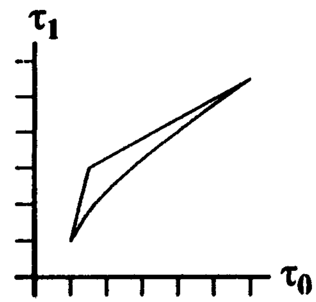
$$\tau_1 = \frac{5}{192} \cdot \left(\frac{c^3}{G \cdot \eta \cdot M}\right) \cdot \left(\frac{743}{336} + \frac{11}{4} \cdot \eta\right) \cdot (\pi \cdot f_o)^{-2}$$

$$M \equiv m_1 + m_2$$

$$\eta \equiv \frac{m_1 \cdot m_2}{(m_1 + m_2)^2}$$



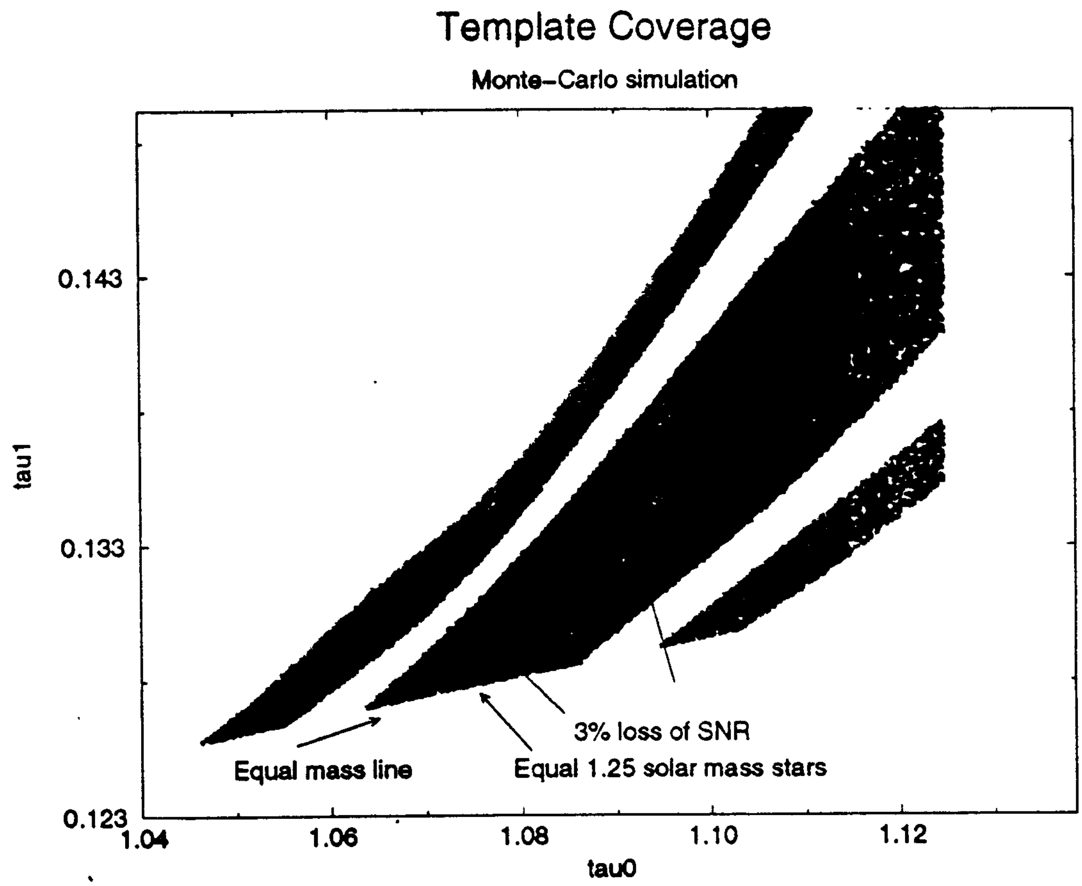




- **templates shaped like ellipses in the coordinates of (τ_1,τ_2)**
- **size and orientation determined by shape of detector noise**
- **location determined by desired ambiguity (~3% used in figure)**
- **Nov. 94 40 meter data needs 403 templates, 0.8 <= (m_1,m_2) <= 50 M_{sun}**

EXAMPLE - `template_spacing` **program**

This does Monte-carlo testing of a filter template. One injects chirps that are "nearby" in parameter space, and calculates the ambiguity function (the loss of SNR).



- The region of fixed ambiguity is an ellipse (for small values of 1-ambiguity), as predicted by theory, but...
- the orientation and size of the template ellipse does not appear to agree with theoretical predictions!

EXAMPLE - `multifilter`

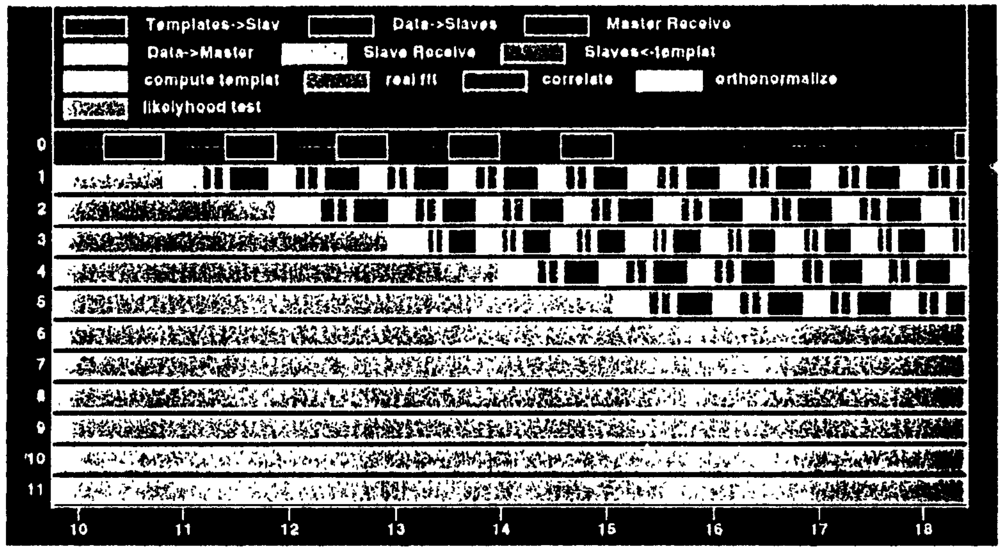
This example program optimally-filters GW data through a bank of filter templates, corresponding to different mass values m_1 and m_2.

- Using the Message Passing Interface (MPI) library for parallel processing
- Master-Slave model. Master hands out sections of data, slaves process this through filters.
- Master collects and organizes results of filtering (max SNR, veto tests, etc).
- Slaves can save templates or recompute them (depending upon how much memory they have).
- Performance: Running on 256 nodes of the Intel Paragon, it is possible to filter 5 hours of data through 66 templates (representing the mass range from 1.2 to 1.6 solar masses) in 5x3600x66x(0.780)/(256x6) seconds = 10.1 minutes.

Plans for 40 Meter Data Analysis

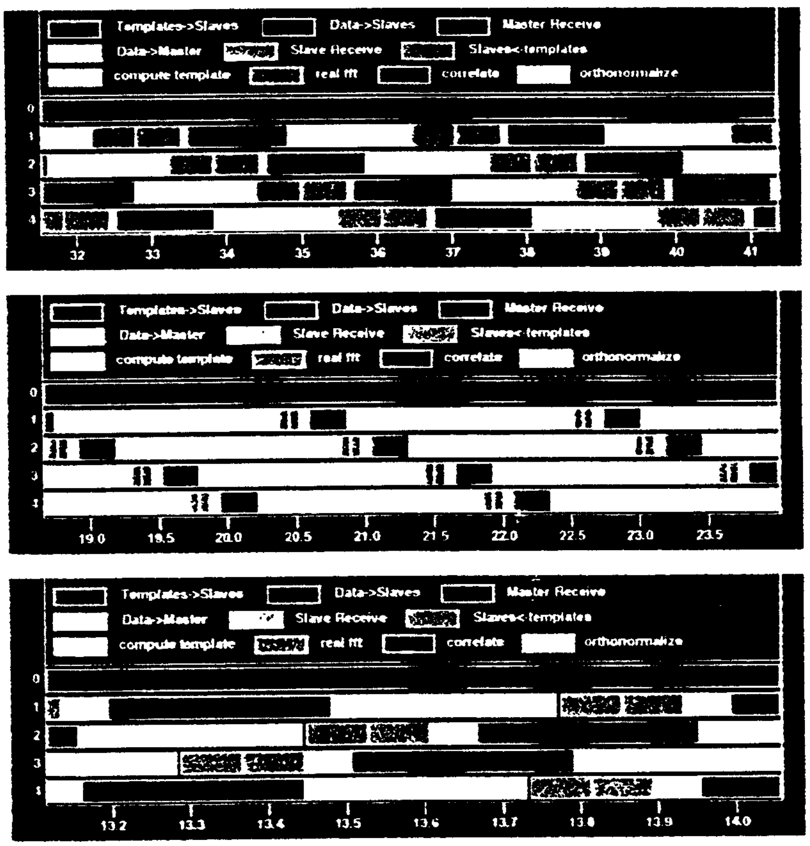
Gravitational Radiation Analysis & Simulation Package (GRASP):

Binary Inspiral Optimal Filtering using MPI



- **optimal filtering code uses the Message Passing Interface (MPI)**
- **MPI provides portability, code tested on SUNs, Paragon and SP2**
- **each node analyzing different date with full template bank used on each node**
- **templates can either be stored and read back or recomputed as needed**
- **spanning 1.2 -> 1.6 solar mass, templates for the Nov. 1994 data needs 66 templates**
- **5 hours of 40 meter filtered by 66 template in 10.3 minutes using 256 nodes on Paragon**

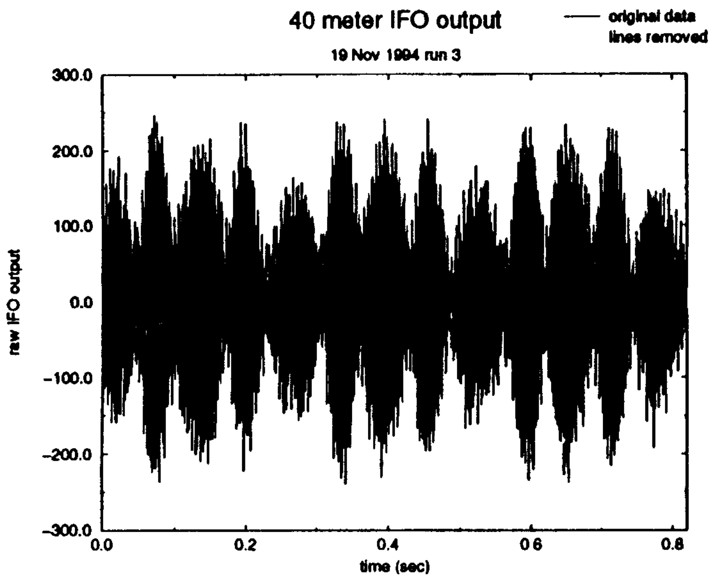
OPTIMIZATION STEPS (Intel Paragon)

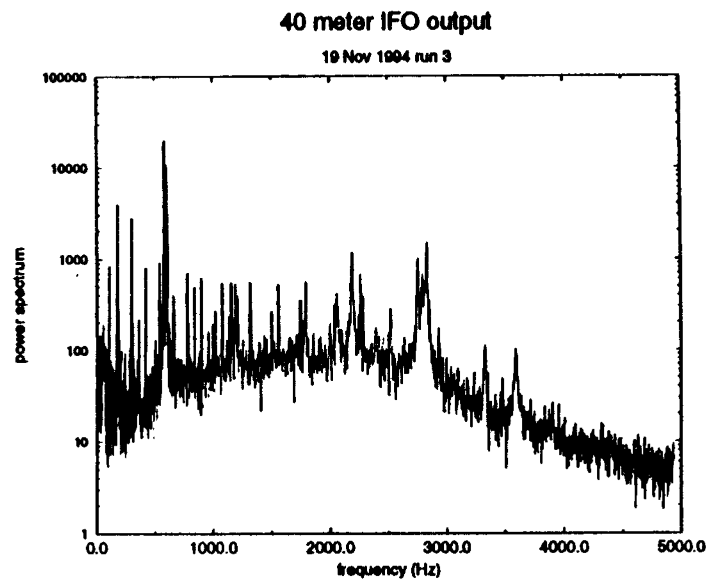


TOP: *Numerical Recipes* FFT routine `realft()`: 4.2 seconds to process 6 seconds of data.
MIDDLE: Uses *CLASSPACK* optimized FFT routine: 2.1 seconds to process 6 seconds of data.
BOTTOM: Inline functions for cube-root and sine/cosine functions: 780 msec to process 6 seconds of data.

Plans for 40 Meter Data Analysis

On-line Analysis: *(Multi-Taper Methods)*

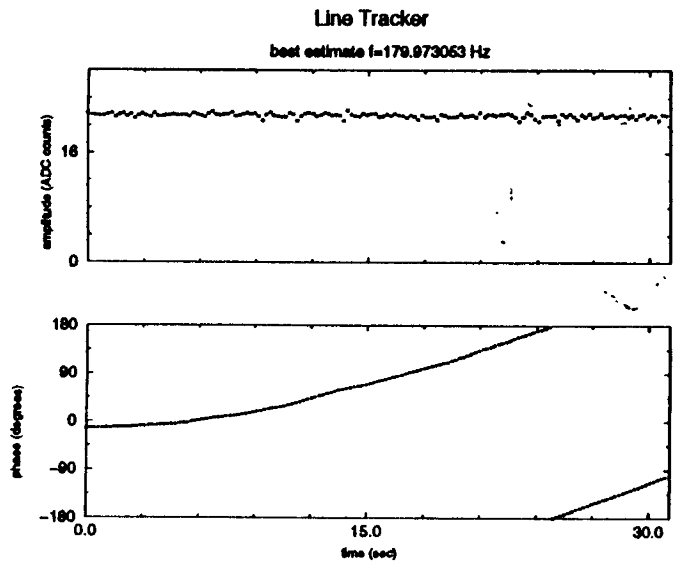


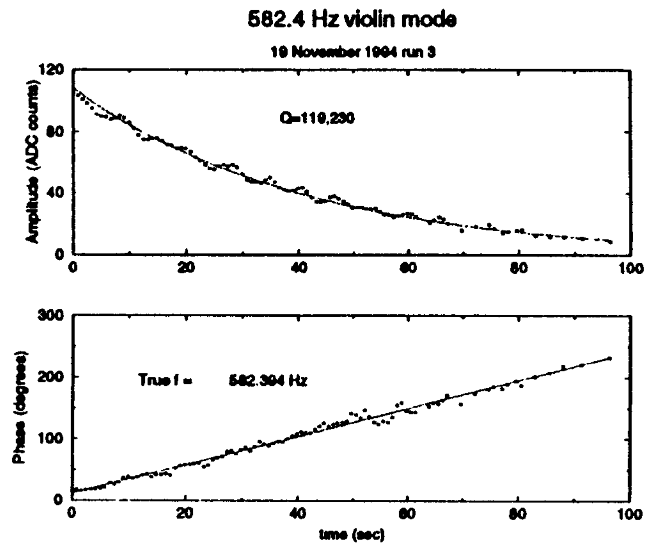


- **Uses multiple sets of special windows called Slepians**
- **39 narrow lines identified and removed in the red plots**
- **Provides better spectral estimation**
- **Provides spectral line parameter estimation and removal**
- **30% improvement in signal to noise ratio after lines removed**

Plans for 40 Meter Data Analysis

On-line Analysis: *(Multi-Taper Methods, cont.)*





- **Useful as a diagnostic tool**
- **Allows track of narrow lines**
- **Using UltraSparcs1 workstation, line can easily be tracked in real time**

Software and Hardware Standards

PAC Meeting - MIT, June 12-13, 1997

Kent Blackburn, LIGO Project

- LIGO needs for Standardizations
- Data Formats
- Software Standards
  - ››ANSI Standards
  - ››Operating Systems
  - ››POSIX Standards
  - ››Styles & Conventions
- Hardware Standards
  - ›› Platforms
- What Next?

LIGO needs for Standardization

- Establish common framework for LIGO data analysis
- Minimize need to target particular software/hardware solutions and environments
- Reduce costs associated with software/hardware systems
- Isolate details of implementation from interfaces
- Provide a direction for future growth
- Minimize maintenance associated with large systems
- Allow LIGO to more efficiently reach its scientific goals with the data analysis system

Data Formats

- LIGO and VIRGO developing common data format for gravitational wave data *(http://lapphp.in2p3.fr/virgo/FrameL)*
  - based on the C language's composite struct type specifier
  - allows sharing of data between the two projects
  - establishes common foundation for data analysis software and algorithms
  - expectations for widespread standardization among other GW programs
- Based on a data format and an I/O library
  - LIGO & VIRGO working on format and library for more than a year
  - used in 40 meter proto-type data acquisition system at Caltech
  - used by GRASP data analysis software to interface with data

Software Standards

ANSI Standards

- The American National Standards Institute X3 committee has published standards for computer languages as guidance to compiler vendors - source code portability

  ›› the ANSI XJ316 committee joined by the ISO WG21 committee in the drafting of the C++ standard

- Large, complex software system generally developed using C and C++
- Inter-operability between C and C++ established through the standard
- LIGO is targeting the OOP paradigm of ANSI C++ language for components of the data analysis system that will require long lifetime and robust behavior

Software Standards

Operating Systems

- Historically hardware and software have been married
  - ›› not so strongly the case with today's OS's, e.g., UNIX and OPENSTEP
- Modern hardware becoming independent of the operating systems
  - ›› multiple OS's available on single hardware platforms, e.g., Windows**, Linux, OPENSTEP... for Intel computers
- UNIX has survived the test of time
- Subtle differences in UNIX flavors impact on the portability of software - solution POSIX standard
- LIGO is targeting UNIX for its data analysis environment

Software Standards

POSIX Standards

- POSIX is the Portable Operating System Interface standard
- Defines the Application Programming Interface to the operating system addressing:
  - base level OS API's for file and process manipulation
  - real-time OS interfaces and inter-process communications
  - standards for multi-threaded (concurrent) processing of code
- By adopting UNIX as the operating system and targeting POSIX compliance in the flavors of UNIX and LIGO data analysis software, the dependency on operating systems can be substantially reduced

Software Standards

Styles & Conventions

- Styles and Conventions can be used to extend the standardization of code
- Styles and Conventions can be used to avoid common "misuses" of the syntax of a computer language
- Most high level computer languages support multiple programming paradigms - software should ideally be limited to just one
- Software styles and conventions can be used to increase the readability of code - easing the maintenance load

Hardware Standards

Platforms

- LIGO data analysis needs are substantial

  ››several hundred GFLOPS needed to search down to theorized ~0.2 solar mass compact binary systems

  ››pulsar analysis would require many orders of magnitude more performance for an all sky survey for expected signal integration times

  ››mass storage needs to carry out these searches are in the GB to TB regime

- Some form of multi-processor / multi-storage system will certainly be used
- Options include clusters of workstation, MPP, SMP, SSMP, parallel machines - code running on 1 or 100 processors

  ››MPI emerging as standard and available for all these options

What Next?

- Establish a specification for the Frame data format
  - ›› involves writing a specification for the data format and functionality
- LIGO must go forward with the design of the data analysis system and continue to proto-type
- The OOP components require the most "front-loading"
  - ›› laying out the communication network
  - ››establish behavior needed by objects and settle on attributes
  - ›› provide clear documentation of the specification, interfaces & conventions
- Designs must cleanly separate the definition from the implementation (declaration), reducing future maintenance

LIGO Analysis Systems

On-line (A. Lazzarini)

Off-line (T. A. Prince)

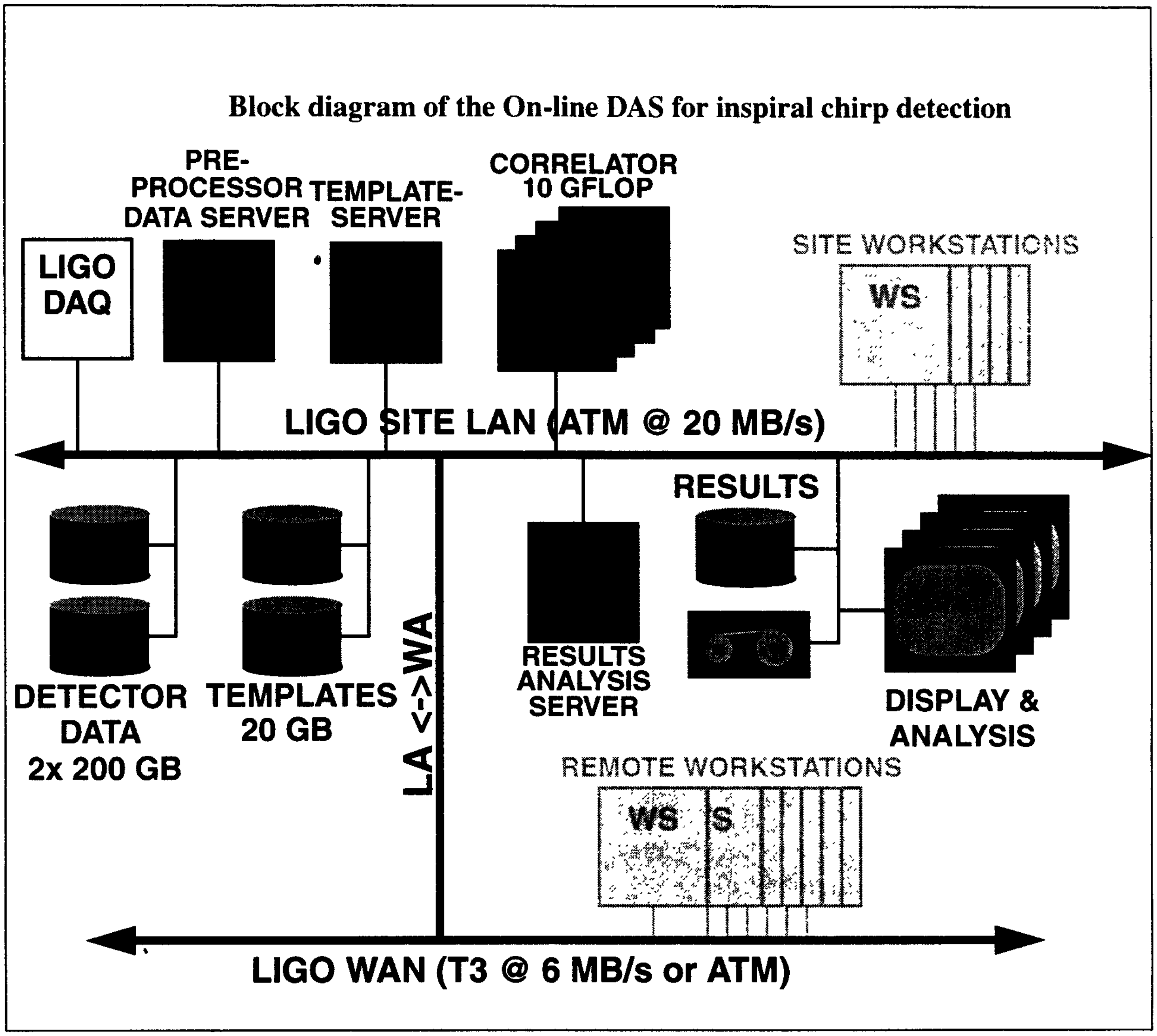
DAS Conceptual Approach
on line component

- Provide adequate on-line capability to support sites independently
  - ›› During commissioning phase, system will be used for diagnostics:
  - ›› Provide required computational capacity to support exploration and discovery phase of instrumental behavior
    - — Instrument correlations; environmental sensitivities; noise source classification/removal; sensitivity improvement;
    - — Identify regression scheme to reduce data
  - ›› WAN access to data for university analyses
    - — Analyses performed locally on workstation cluster (cannot bog down on-line system) or remotely by transferring data blocks (compressed)
  - ›› During LIGO I science run, on-line system will provide computational capacity to perform needed searches
  - ›› Process GW datastream (suitably conditioned) for chirp detection
    - — Lower detectable mass limit set by resources
      - **$m>1\ M_{solar}$ IS FEASIBLE WITH 3.6 GFLOPS/INTFEROMETER**
      - **2km & 4km MACHINES REQUIRE DIFFERENT TEMPLATE DICTIONARIES**
      - **USE THE CDS/DAQ MASS STORAGE ARRAY (AUGMENTED, IF REQUIRED) FOR CACHE SPACE AT THE SITES - 400 GB (200 GB FOR LA)**
        - **storage of 9 hours of 100% data stream**
        - **storage of 10 *weeks* of GW channel only**

DAS Conceptual Approach
on line component

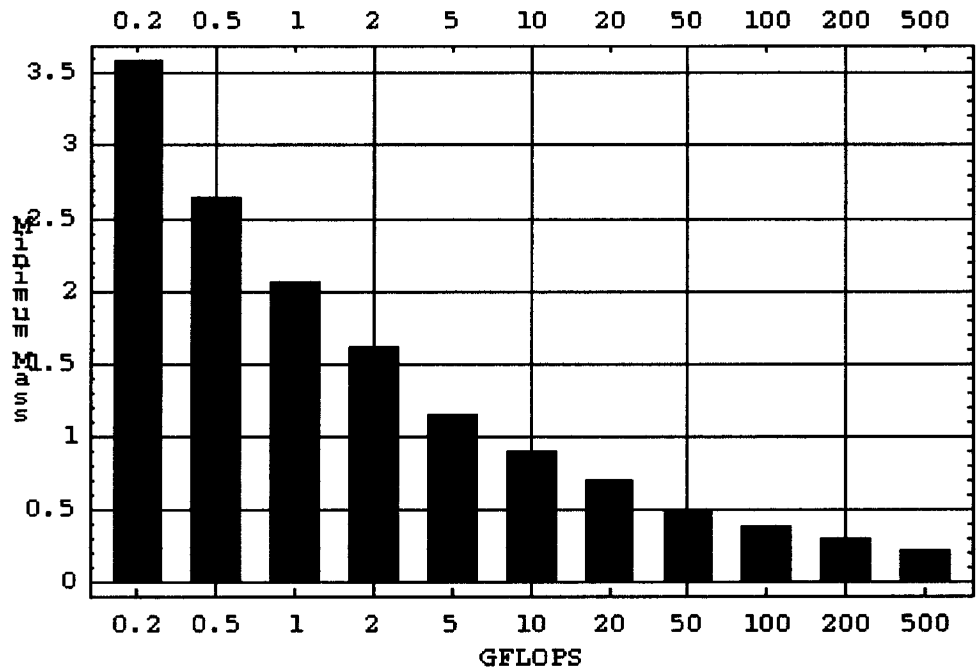
- Process GW datastream for transient (burst) events
  - likely (initial) techniques involve (short) wavelet templates to efficient capture transient waveform behavior
  - compare signal characteristics against dictionary of catalogued waveforms for vetoing
  - site-to-site datastream cross-correlation for short periods of time - driven by triggers with sufficient SNR excedence on each instrument
- Utilize inspiral template filter bank performance output as an end-to-end machine performance metric
  - Noise statistics -- non-stationarity
  - False alarm rate
  - Secular drift in sensitivity
  - etc.

On-line hardware configuration



Dependence of computational capacity requirement on minimum compact object mass for binary inspiral detection

Minimum detectable mass (solar mass) versus computer processing power (GFLOPS) for two interferometers operating simultaneously (Hanford site)

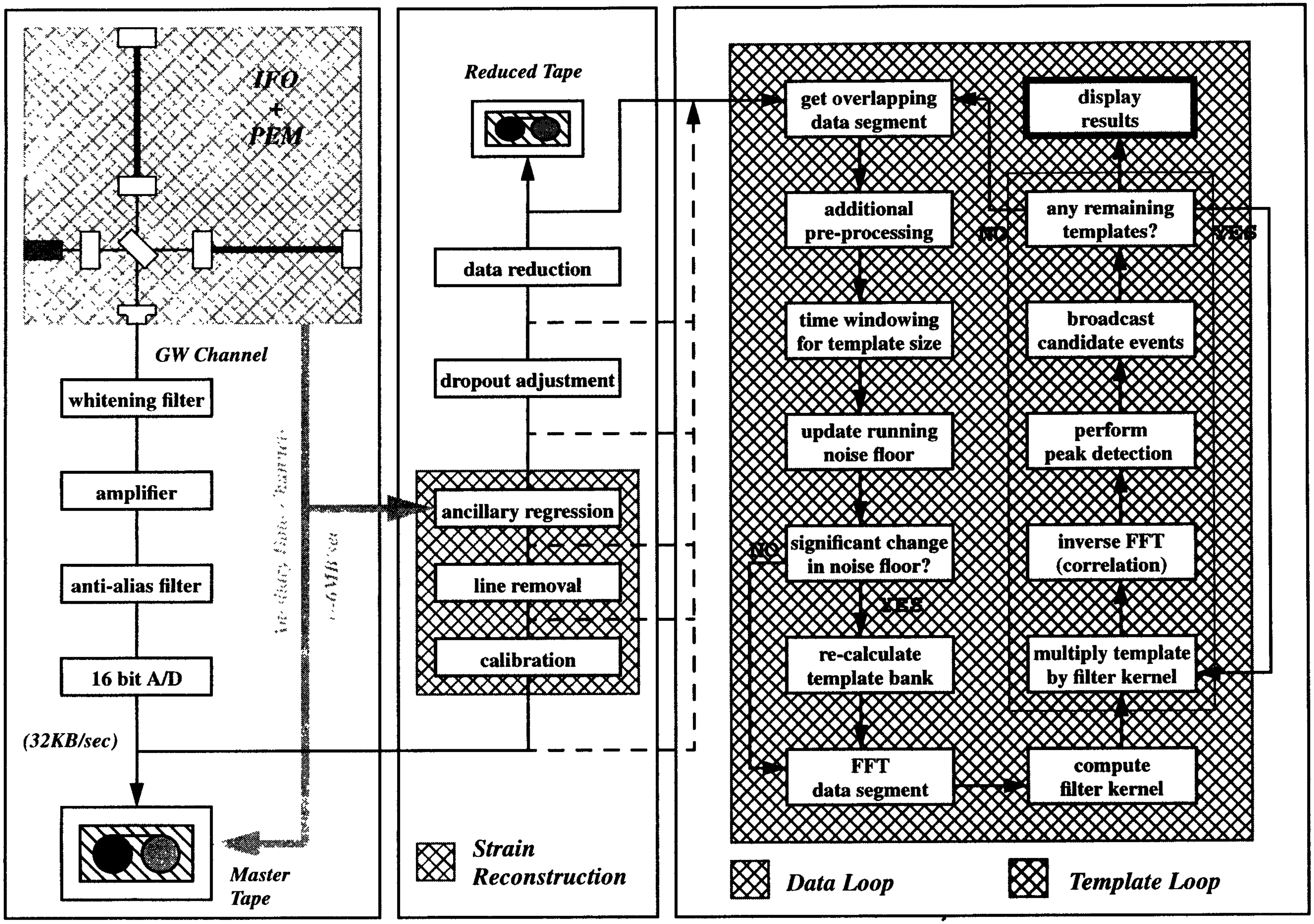


Source: model of inspiral binary data flow (*sans* regression component); including OS overheads; I/O limitations (memory swaps) ; RAM limitations; cache limitations; FFT and Mult-Acc. counts; etc.

DAS Conceptual Approach
off line component

- Off-line capability provided through CACR
  - ›› data archive
  - ›› final reduction of datasets
    - final calibration
    - cross-correlation with other channels
    - regression (if needed)
    - dewhitening
    - compression
    - data QA flags
  - ›› high bandwidth access by remote researchers
    - LIGO Laboratory: MIT, Hanford, Livingston
    - Scientific Collaboration: UMW, UO,...
  - ›› CACR hosts analyses and provides results
    - inspiral searches to lighter binary masses
    - periodic source searches
      - INITIALLY DIRECTED AT SPECIFIC TARGETS
    - other analysis techniques
  - ›› connectivity via Wide Area Network
  - ›› model for interaction and research with CACR being formed through experience with prototyping activities

Data analysis conceptual flow: binary inspiral and coalescence events



LIGO/CACR Collaboration

Advanced Facilities for
Analysis, Archiving, and Networking
of LIGO Data

Prof. Thomas Prince
Member of the LIGO Project
Associate Director CACR

LIGO

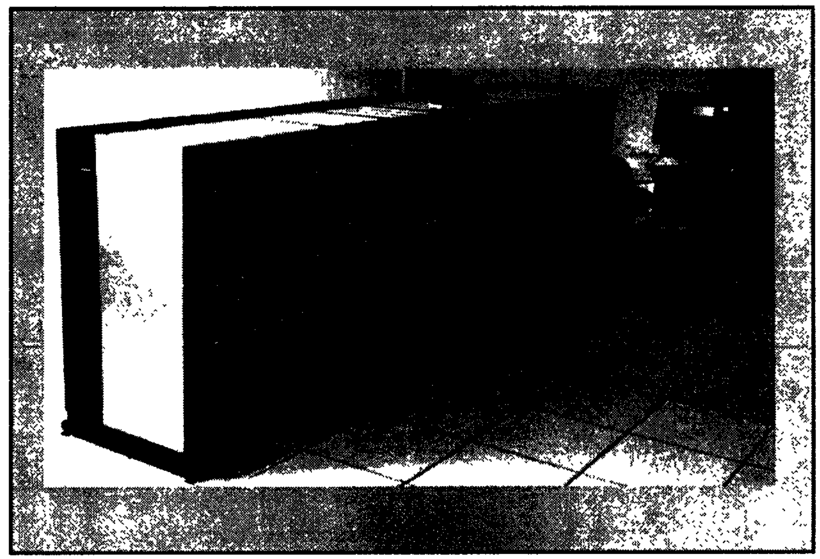
What is CACR?

- CACR: Center for Advanced Computing Research at Caltech
  - A major partner in the NSF NPACI (National Partnership for Advanced Computing Infrastructure) recently selected as one of two national supercomputing consortia
  - Significant expertise in parallel computing and networking
  - Major existing facilities for data intensive computing:
    - Compute engines: 512 processor Intel Delta, 512 processor Intel Paragon, 16 processor IBM SP-2, 64 processor HP/Convex Exemplar.
    - 30 Terabyte HPSS (High Performance Storage System)

LIGO

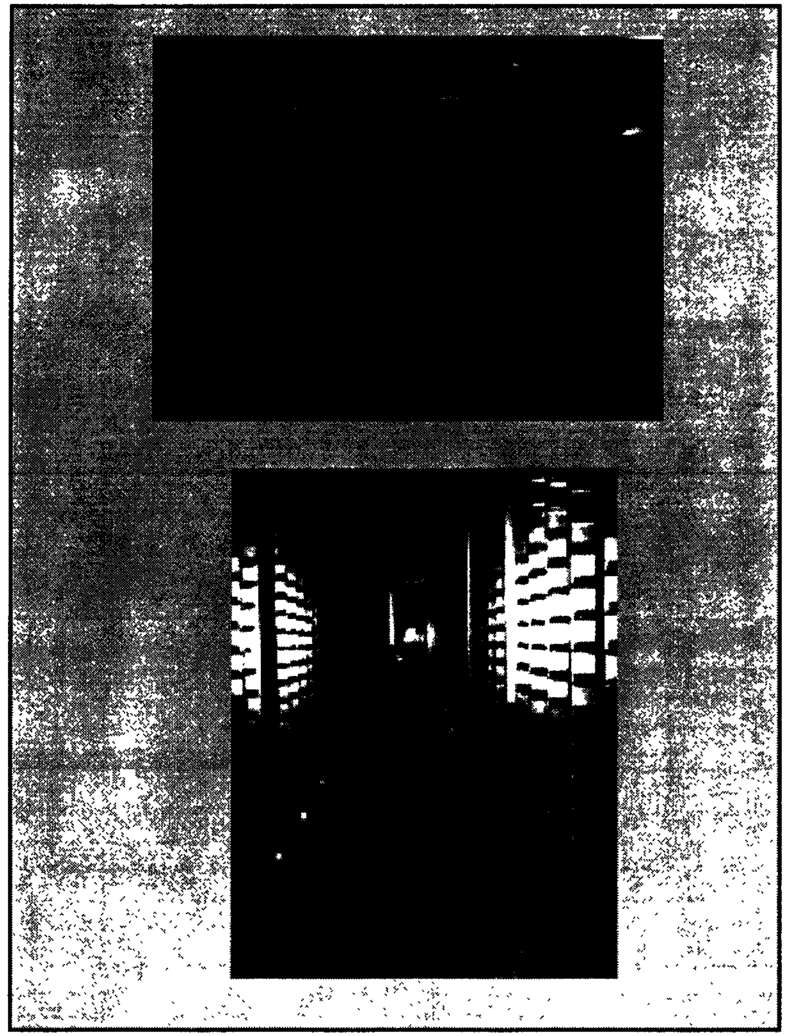
CACR Computing Facilities

- Current Facilities
  - Approximately 30 Gigaflops
    - 512 node Intel Delta
    - 512 node Intel Paragon
    - 64 node HP/Convex SP2000
    - 16 node IBM SP-2
- Future Facilities
  - Advanced HP/Convex: 300 Gigaflops



CACR Facilities: HPSS

- 30 Terabyte Tape Robot
  - 4 Tape Drives
  - 2400 Tape Cartridges
- 144 Gigabyte Disk Cache
- HiPPI network interface (25 MByte/s)



LIGO

LIGO/CACR Relationship

- CACR ***is not*** a computer center
- CACR ***is*** a federation of research projects
  - In addition to LIGO, examples include:
    - Astronomy: IRAS Galaxy Atlas and Digital Sky Project
    - Earth Sciences: Synthetic Aperture Radar Analysis
    - Computational Chemistry, Biology, Fluid Mechanics
- CACR will collaborate with LIGO in design and test of prototype system architectures
  - Ongoing activities:
    - Development of parallel codes for FFT simulation
    - Development of parallel codes for binary inspiral analysis
    - Network based archiving and data access using HPSS
    - Prototype distributed computing environment (Paraflow)

LIGO

Future Directions

- LIGO will implement significant compute facilities in collaboration with CACR
  - Parallel computers for intensive analysis tasks
    - Inspiral of low-mass objects
    - Large area sky searches for periodic signals
  - High-capacity archiving and high-throughput data access
- Models
  - Time-sharing on CACR resources
  - Dedicated LIGO resources housed at CACR to take advantage of expertise and infrastructure

LIGO

LIGO WIDE AREA NETWORK (WAN)

Approach & Status

LIGO Wide Area Network (WAN)

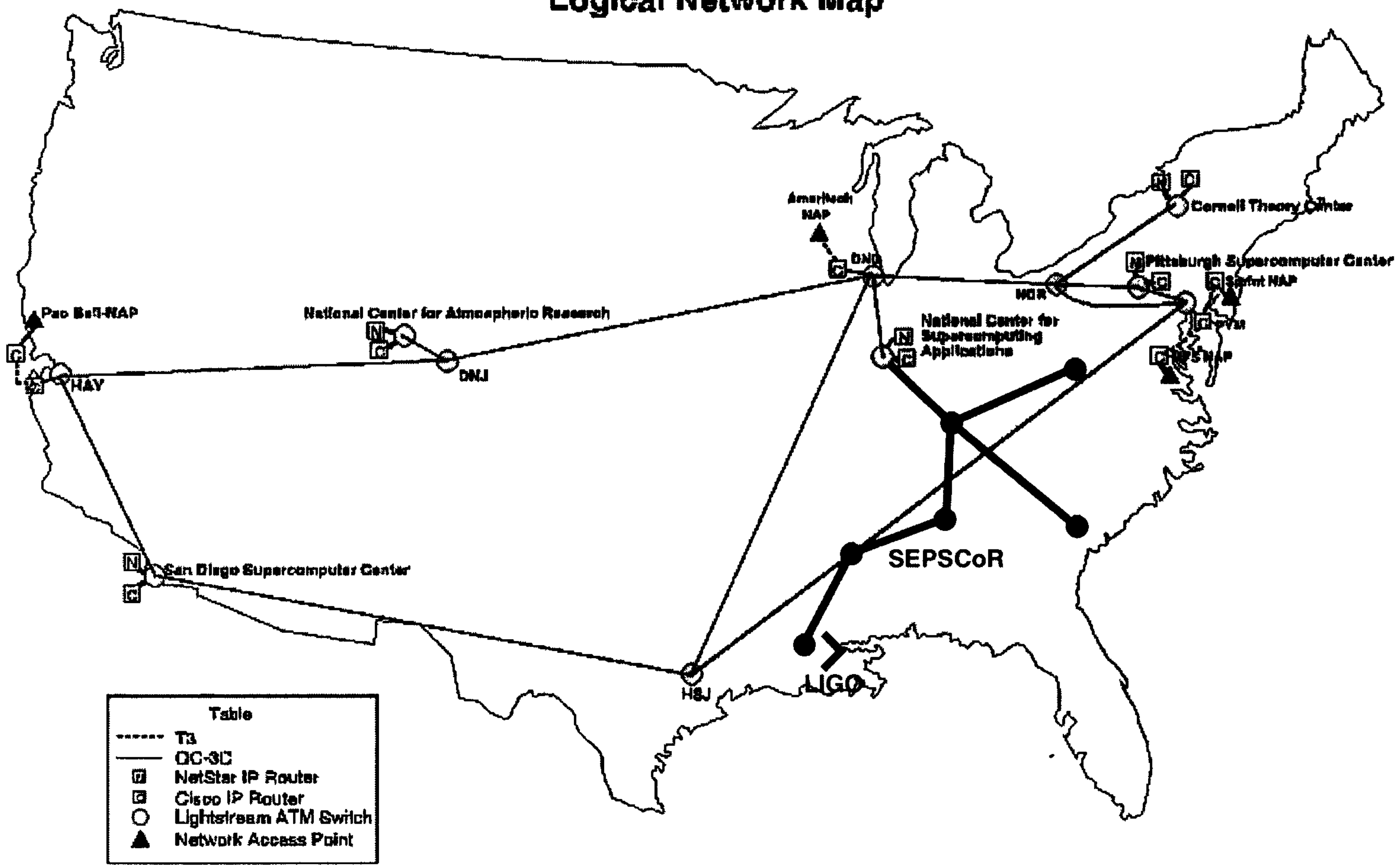
- LIGO Wide Area Network supports LIGO Laboratory Operations
  - Access to University resources (CIT/MIT) from observatories
  - Access to LIGO database @ CIT/MIT
  - Access to off-line data analysis component
  - Observatory-to-observatory communications
  - Access by Universities to recent data (quasi-real time)
- WAN provides access to data archives for the Scientific Collaboration
- LIGO is working in conjunction LSU, DOE/PNNL to set up arrangements
  - LSU presently providing ISDN service to Livingston site during construction
  - LIGO has provided letter of intent to support/utilize vBNS connection at LSU
  - DOE has been approached through contacts at Battelle PNNL

LIGO Wide Area Network Plan

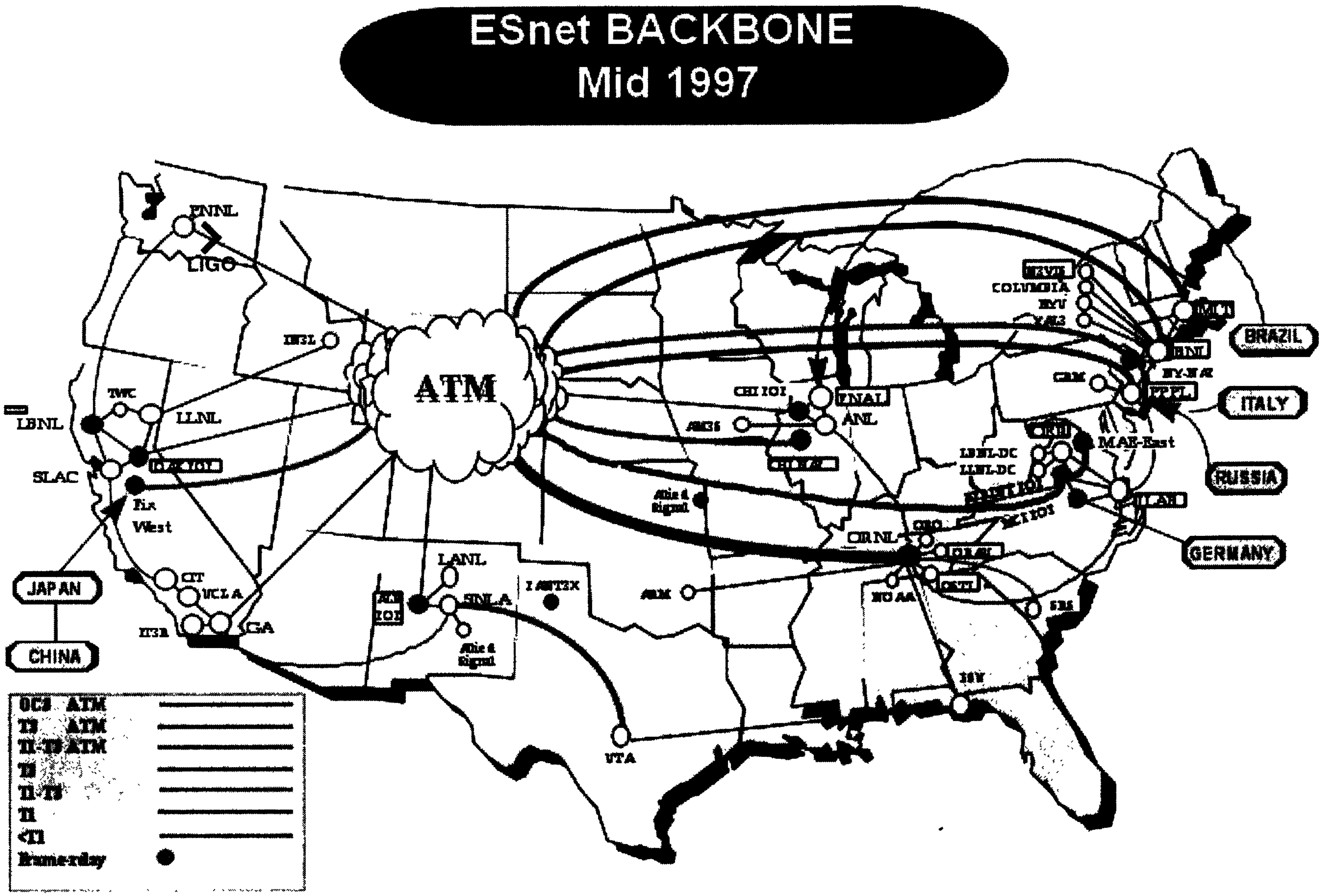
- Utilize, wherever possible, the future NSF vBNS backbone:
  - ›› LIGO Laboratory:
    - MIT - vBNS access announced 97.22.05
    - Caltech (NPACI/CACR) - vBNS access announced 97.22.05
    - Livingston Observatory -- LSU
      - **Site proposal provisions include access to university resources for LIGO**
      - **LSU member of SouthEast Partnership for Shared Computational Resources (SEPSCoR) - proposal pending for vBNS access through UKy -** - vBNS access (UKy segment only) announced 97.22.05
  - ›› Collaborating institutions expected to provide communications access for their researcher to access LIGO Laboratory resources
- LIGO/Hanford will be connected through ESnet
  - ›› Link through Battelle/Pacific Northwest National Laboratory (PNNL)
  - ›› Working with PNNL computing services administration
  - ›› ESnet links PNNL to ATM cloud (there is a backup link to LBNL/LLNL -> SLAC) -> Caltech (HEP)
  - ›› PNNL may obtain vBNS access directly through its NPACI participation - details not yet known (in LIGO).
- Hanford-Livingston connection would be via Caltech (possibly MIT as a backup) if ESnet is used.

NSF's vBNS Infrastructure will allow LIGO Livingston to link up with other Laboratory Sites via NCSA and Louisiana's regional access via SEPSCoR to vBNS (added to map; NSF map is from mid 1996)

The National Science Foundation Very-High-Speed Backbone Network Service
Logical Network Map



DOE's ESnet Infrastructure will allow LIGO Hanford to link up with other Laboratory Sites via PNNL
(LIGO has been added to map)



Plans for the new lab and schedule for the relocation

Richard Benford

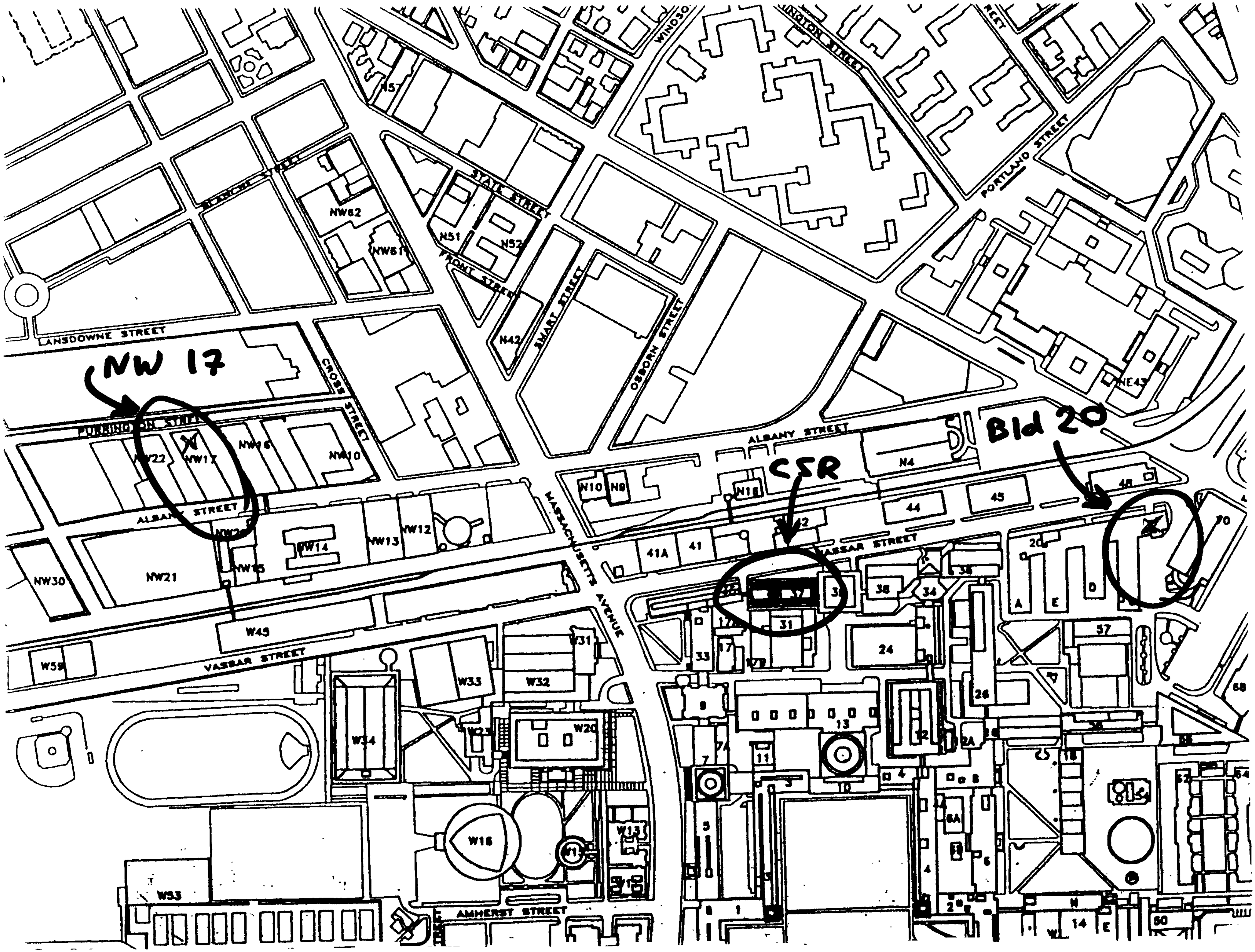
General.

MIT is committed to relocating the LIGO group from Building 20 to NW17.

MIT is also committed to a larger high bay space for the antenna system.

Other areas, offices and labs will be about the same size as now.

Where is NW17 in relation to current space?


NW 17
Bld 20
CSR
LANSDOWNE STREET
PURRINGTON STREET
ALBANY STREET
VASSAR STREET
CROSS STREET
STATE STREET
FRONT STREET
SMART STREET
OSBORN STREET
PORTLAND STREET
MASSACHUSETTS AVENUE
AMHERST STREET
NW62
NW61
N51
N52
N57
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LIGO Specifications.

High Bay Area:

Larger area ~4,000 sq. ft. to accommodate 16m antenna. (Current high bay area is around 1,200 sq. ft.)

Active seismic isolation devices will be employed at each tank. A study is currently being done on the soil conditions and the building structure. We expect a resolution to this shortly.

High Bay Area will use "clean" laboratory finishes.

Lab Areas:

Support labs will be the same size as currently in Building 20.

But by better design and use of NW17 a greater efficiency of space to the labs is achieved over building 20.

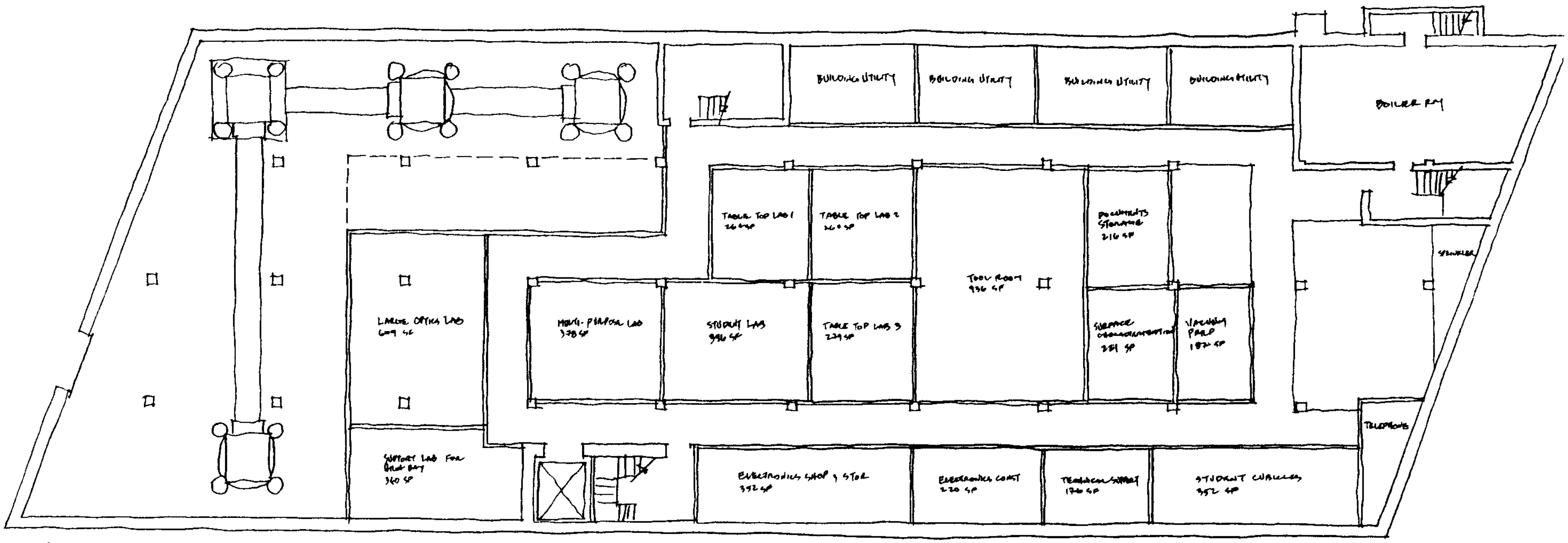
Optics labs and high bay support labs will use "clean" laboratory finishes.

Other labs will be standard labs.

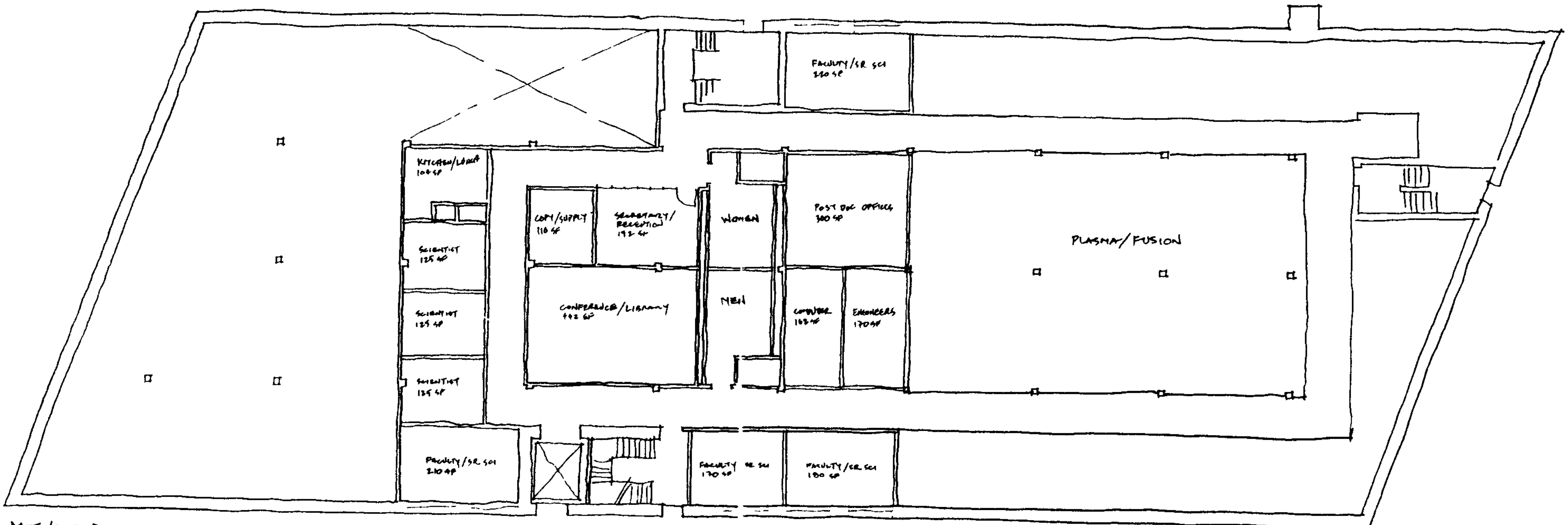
Office Areas:

Offices will be about the same size as in 20.

All areas will conform to current codes, e.g. ADA rules, fire codes, etc.



MIT/LIGO (SCHEME 3A)
LOWER LEVEL PLAN
1/8" = 1'-0"



MIT/LIGO
FIRST FLOOR PLAN (SCHEME 3A)
1/8"=1'-0"

<u>LIGO Relocation Schedule.</u>

Building 20 is scheduled to be razed in March '98.

The LIGO group is expecting a move to NW17 in late January, early February '98.