NASA'S TERAHERTZ TECHNOLOGY PROGRAM

DR. MARTIN SOKOLOSKI
Department of Physics
Drexel University
and
Office of Aeronautics, Exploration and Technology
NASA Headquarters

DR. CARL A. KUKKONEN
Director
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology

Abstract

NASA is developing submillimeter (terahertz) receivers for use in astrophysics, the study of planetary atmospheres and for Earth observation. The science objectives include the understanding of star formation, the interstellar medium, galactic formation, the composition of planetary atmospheres, and ozone depletion in the Earth's atmosphere. Since the Earth's atmosphere is opaque in most of the submillimeter region, observations must be done from space.

Because submillimeter technology has no significant ground applications, the receiver technology is not available. The NASA Office of Aeronautics, Exploration and Technology is vigorously pursuing a multi-year effort to develop the components needed for a submillimeter heterodyne receiver. The critical components include the antenna, local oscillator and mixer. The technical challenges arise due to the high frequency and short wavelength of the radiation.

Because waveguides and waveguide arrays are difficult to fabricate at these wavelengths, quasi-optical antenna techniques are being actively pursued. The local oscillator is a major challenge, because a terahertz is an order of magnitude higher than frequencies obtainable with conventional electronics. Novel structures such as resonant tunneling devices are used as fundamental oscillators and as frequency multipliers.

The mixer elements being investigated are solid-state planar Schottky diodes for Earth observations and superconducting-insulating-superconducting (SIS) tunnel junctions for low-noise cryogenic astrophysical telescopes.

The University of Michigan Center for Space Terahertz Technology was established by NASA to help develop additional expertise and students trained in this area.

The National Aeronautics and Space Administration (NASA) is developing submillimeter (terahertz) receivers for use in astrophysics, the study of planetary atmospheres and for Earth observation. The science objectives include the understanding of star formation, the interstellar medium, galactic formation, the composition of planetary atmospheres, and ozone depletion in the Earth's atmosphere. Since the Earth's atmosphere is opaque in most of the submillimeter region, observations must be done from space.

For reference, the wavelength of 1 THz (1000 GHz) radiation in free space is one-third of a millimeter or 333 μm. The frequency is 30 times higher than "standard radio waves" used in radars, yet 30 times lower than the frequencies of "standard infrared photons." Technology is available for radar frequencies and detectors are also available in the infrared. However, the technology needed for the terahertz region (0.3-30 THz) has not yet been developed.

There are two reasons for the lack of technology. First, the frequency regime is intrinsically very difficult. The photon energies are small relative to the energy gaps of opto-electronic semiconductors, but the frequencies lie beyond the frequency range accessible with conventional semiconductor electronic devices. Secondly, since the Earth's atmosphere is largely opaque in the terahertz region, there has not been a demand for terahertz receivers for terrestrial applications, and there is no current commercial application of terahertz technology.

The terahertz frequency range is important to NASA because molecular species important in atmospheric chemistry, such as ozone and chlorine oxide, and other molecules found in the interstellar medium, have radiative emissions in this range. The sharp emission lines can be detected readily by a heterodyne receiver. The frequency of an emission line identifies the species; the intensity gives abundance, and the relative intensity of two lines from the same molecule yields the temperature. In addition, Doppler-shifted deviations from laboratory spectra gives information about the dynamics of the interstellar medium.

The NASA Office of Aeronautics, Exploration and Technology is developing technology for potential future terahertz space missions such as the ozone depletion experiment on the Earth Observing System (Eos), the Submillimeter Explorer, the Submillimeter Imaging Line Survey and the Large Deployable Reflector. The focus is on solid-state receiver components that are compact, low power and space-qualifiable.

Limited terahertz data can be obtained from the Earth by observing from high mountains, balloons or aircraft to get above much of the atmosphere, and using frequency bands where the atmospheric absorption is minimum. These Earth-based observations allow the technology to be demonstrated in real systems before actual use in space.

The technology needed to study ozone depletion of the Earth's atmosphere differs from that needed for astrophysics. In ozone depletion studies, the atmospheric signal strength is relatively large, but accurate measurements must be made continuously for 5-10 years to detect small changes. The long mission lifetime precludes the use of stored cryogen refrigeration and dictates that receivers must operate at 65-125K. This leads to a requirement for semiconductor mixers, local oscillators and multipliers, which have limited sensitivity.

A major effort is devoted to improving semiconductor Schottky diode mixer efficiency, and extending performance to higher frequencies. The Microwave Limb Sounder, to be flown on the Upper Atmosphere Research Satellite (UARS) in 1992, operates at 200 GHz. The Eos experiment will be at 650 GHz. Schottky diode mixers require substantial local oscillator power, and this is also a major challenge at 650 GHz.

The signal strengths for astrophysics missions are very small, and ultimate sensitivity is required. This dictates large antennas, and ultra-low noise receivers. Most astrophysical missions will need to carry liquid helium to accommodate use of ultra-sensitive superconducting mixers. The mixer is a superconducting-insulating-superconducting tunnel junction coupled with the appropriate tuning elements. Lead-based tunnel junctions have been demonstrated on Earth, but lead junctions have very short life time and cannot be space qualified. The focus of the development effort is on niobium nitride, which is a refractory material and NbN junctions have extremely long life. Currently NbN mixers have shown good performance to 200 GHz, with a theoretical limit of 1.5 THz. The major advantages of super-conducting mixers are that they have extremely low noise and require much lower local oscillator power than a Schottky diode mixer.

Since astrophysical quantities are not changing rapidly, the mission life requirement is dictated only by the level of "sky search" desired. The science return will be significantly enhanced by array technology being developed by NASA, which will allow arrays of submillimeter receivers to take data in parallel. Current receivers, operating up to 200 GHz or so, all use waveguide technology inherited from the radar community. It is difficult to machine waveguides for terahertz frequencies and it is even more difficult to build waveguide arrays. This is the motivation for the NASA effort in quasi-optical approaches, which utilize lenses, and integrated antenna/mixer structures to facilitate arrays.

NASA

NASA TERAHERTZ (SUBMILLIMETER) TECHNOLOGY PROGRAM

Martin Sokoloski
Department of Physics and Atmospheric Science
Drexel University
and
Office of Aeronautics and Space Technology
NASA Headquarters

and

Carl Kukkonen
Center for Space MicroelectronicsTechnology
Jet Propulsion Laboratory

CSMT

NASA TERAHERTZ TECHNOLOGY PROGRAM

- WHY OBSERVATIONS FROM SPACE ARE REQUIRED

- SUBMILLIMETER SCIENCE OBJECTIVES
  - OZONE DEPLETION IN EARTH'S ATMOSPHERE
  - PLANETARY ATMOSPHERES
  - STAR FORMATION AND INTERSTELLAR MEDIUM
  - GALACTIC FORMATION
  - COSMOLOGY

- CANDIDATE NASA MISSIONS
  - GROUND-BASED
  - AIRCRAFT AND BALLOON
  - SPACECRAFT
  - LUNAR BASE

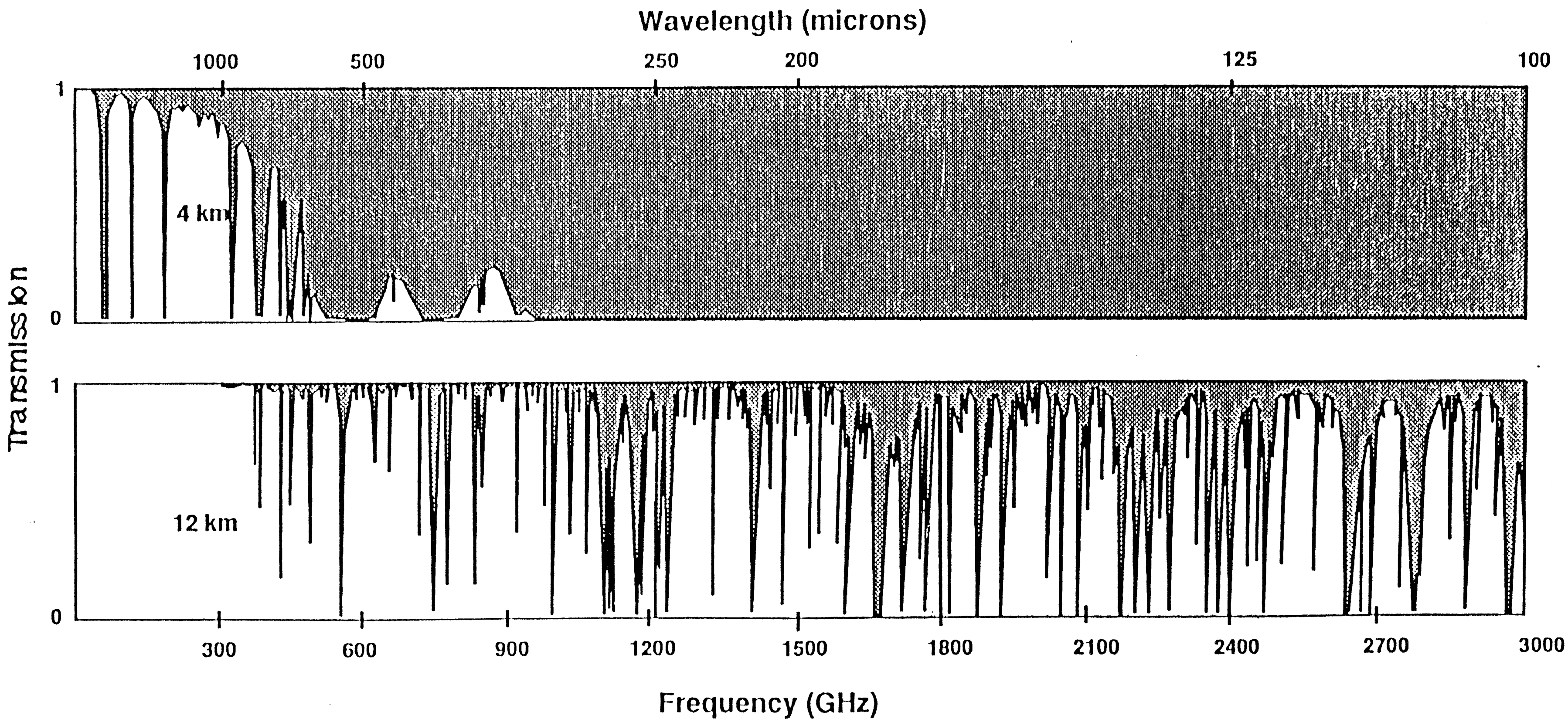
- NASA SUBMILLIMETER SENSOR PROGRAM
  - HETERODYNE RECEIVER COMPONENTS
    - ANTENNAS AND ARRAYS
    - MIXERS
    - LOCAL OSCILLATORS AND MULTIPLIERS

JPL

SUBMILLIMETER ASTROPHYSICS PROGRAM

ATMOSPHERIC OPACITY

- MOST OF SUBMILLIMETER BAND IS UNOBSERVABLE FROM EARTH DUE TO ABSORBTION IN THE EARTH'S ATMOSPHERE



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SUBMILLIMETER ASTROPHYSICS PROGRAM

WHY SUBMILLIMETER ASTRONOMY FROM SPACE?

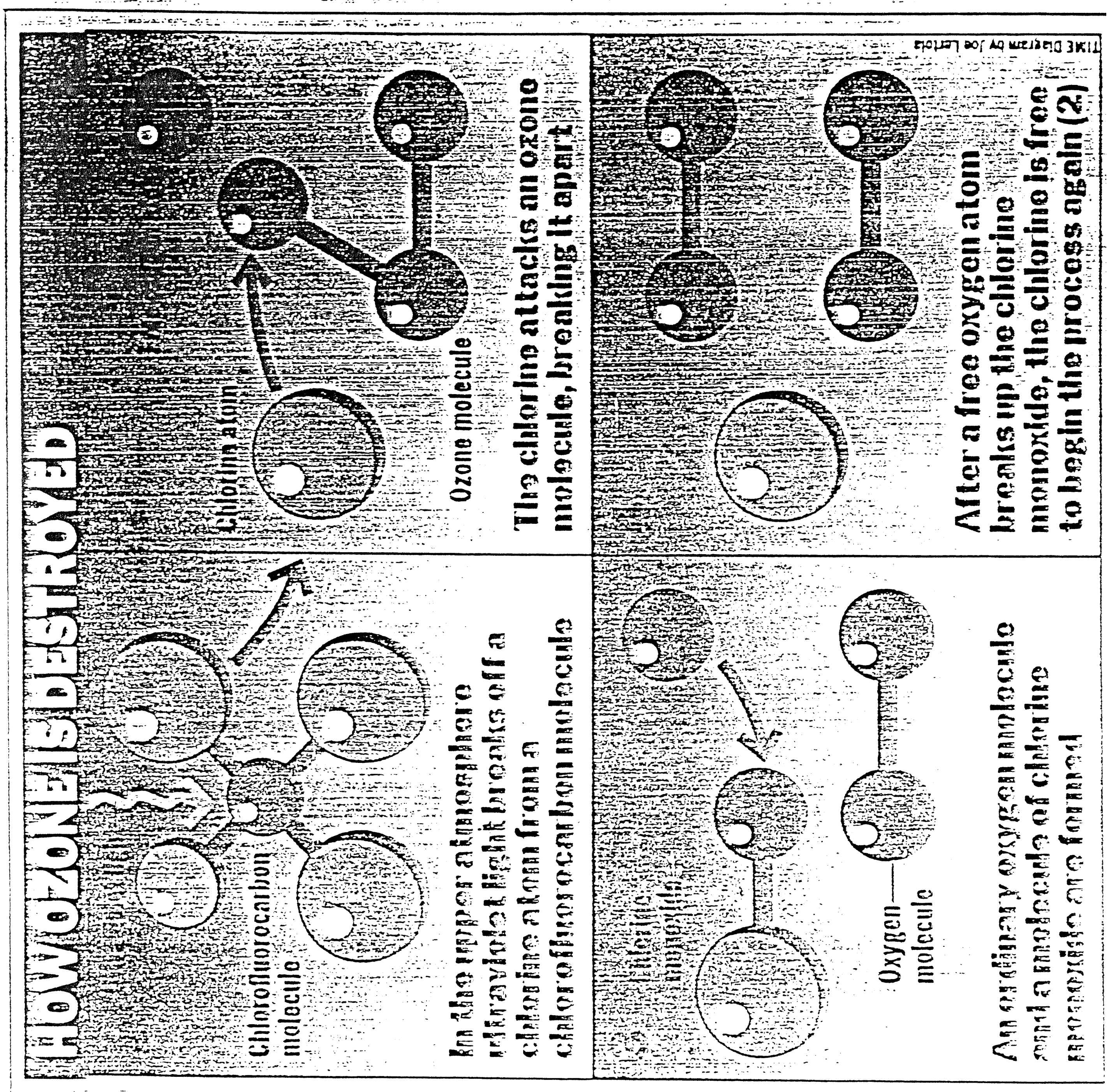
- SUBMILLIMETER OBSERVATIONS FROM THE GROUND RANGE FROM DIFFICULT TO IMPOSSIBLE DUE TO THE EARTH'S ATMOSPHERE
- EMISSION FROM COLD BODIES IN UNIVERSE PEAKS IN SUBMM SPECTRAL REGION
- PROBES REGIONS WHERE VISIBLE RADIATION IS OBSCURED BY DUST
- SPECTROSCOPY OF MOLECULES CAN DETERMINE COMPOSITION, DENSITY, TEMPERATURE, VELOCITY AND DYNAMICS
- VISIBLE AND INFRARED SPECTRUM OF DISTANT OBJECTS IS RED SHIFTED INTO THE SUBMILLIMETER

OZONE DEPLETION

- SINGLE HETERODYNE RECEIVER AT ~ 650 GHz CAN SIMULTANEOUSLY MEASURE
  - OZONE
  - ClO THE KEY MOLECULE WHICH DESTROYS OZONE
  - HCl THE KEY MOLECULE BY WHICH CHLORINE IS REMOVED FROM THE STRATOSPHERE

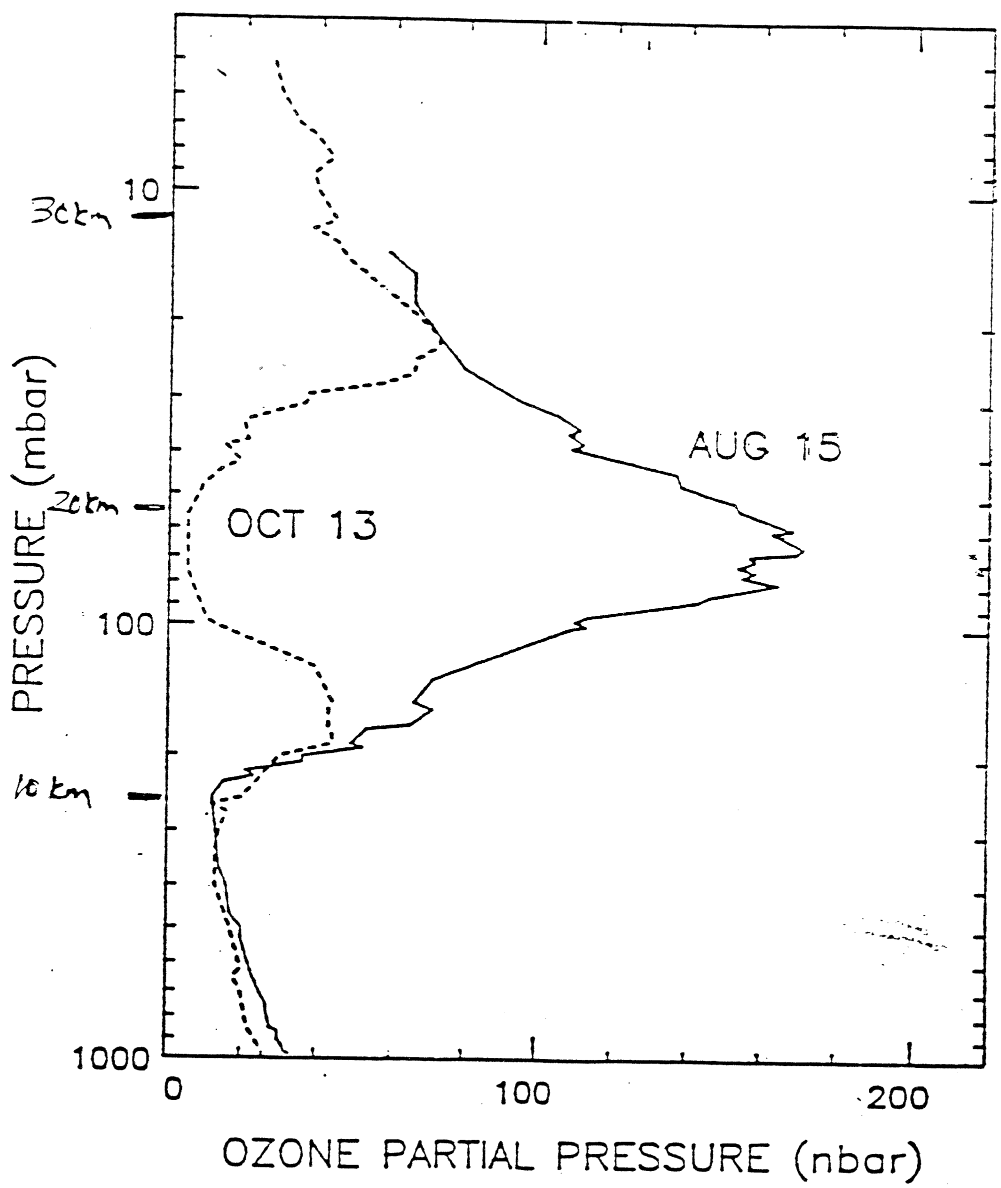
<u>1 FREE CHLORINE ACTS AS A CATALYST AND DESTROYS 10,000 OZONE</u>

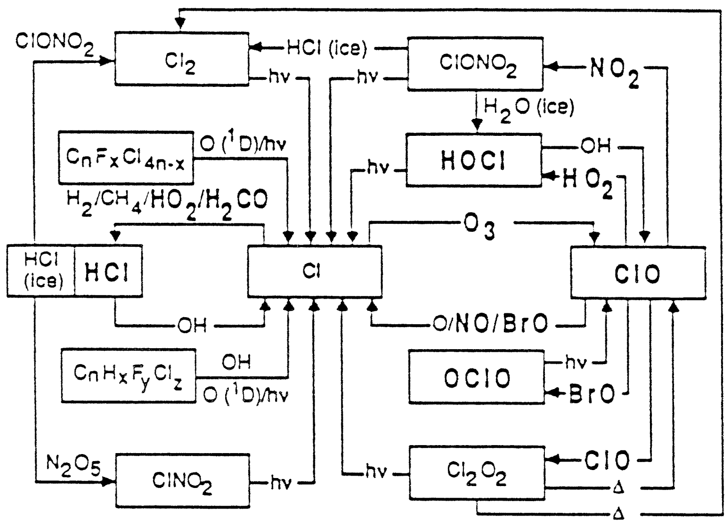
- MUST MEASURE VERY ACCURATELY AND FOR A LONG TIME
  5 + YEARS
- LONG LIFE MISSION CANNOT USE HELIUM COOLED SIS MIXER AND MUST USE SCHOTTKY DIODE
- OZONE INSTRUMENT - MICROWAVE LIMB SOUNDER ON UARS (200 GHz) and EOS-B (650 GHz) . . . JOE WATERS P.I.


HOW OZONE IS DESTROYED
Chlorofluorocarbon molecule
In the upper atmosphere ultraviolet light breaks off a chlorine atom from a chlorofluorocarbon molecule
Chlorine atom
Ozone molecule
The chlorine attacks an ozone molecule, breaking it apart
Oxygen molecule
An ordinary oxygen molecule and a molecule of chlorine monoxide are formed
After a free oxygen atom breaks up the chlorine monoxide, the chlorine is free to begin the process again (2)

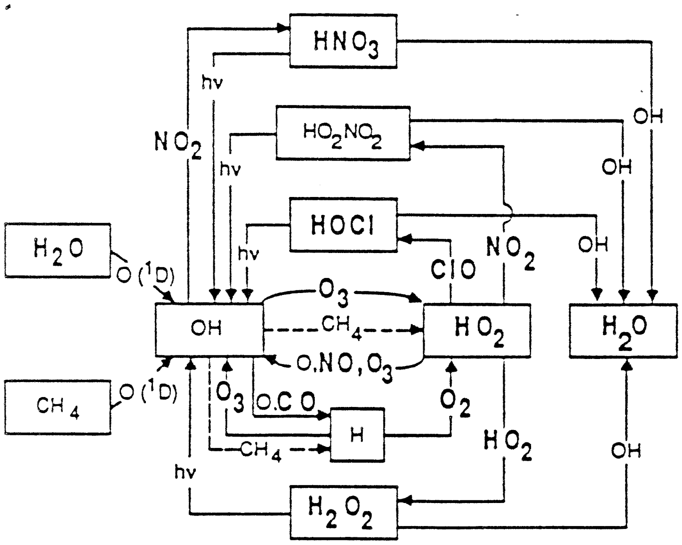
1987 Ozonesonde Measurements from Halley Bay, Antarctica

(from Joe Farman 7 Dec 87)

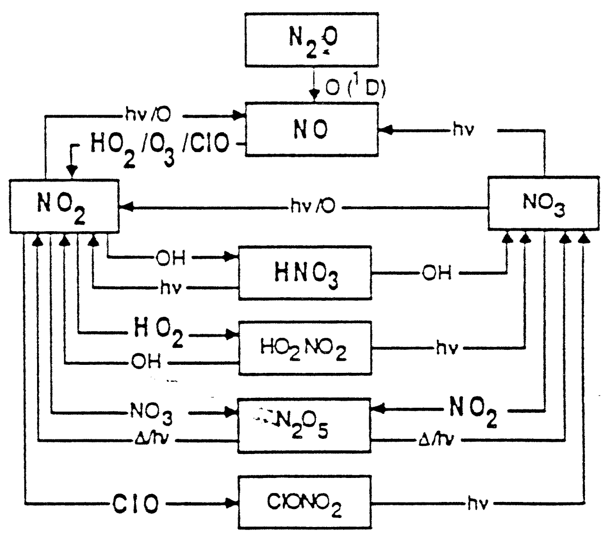




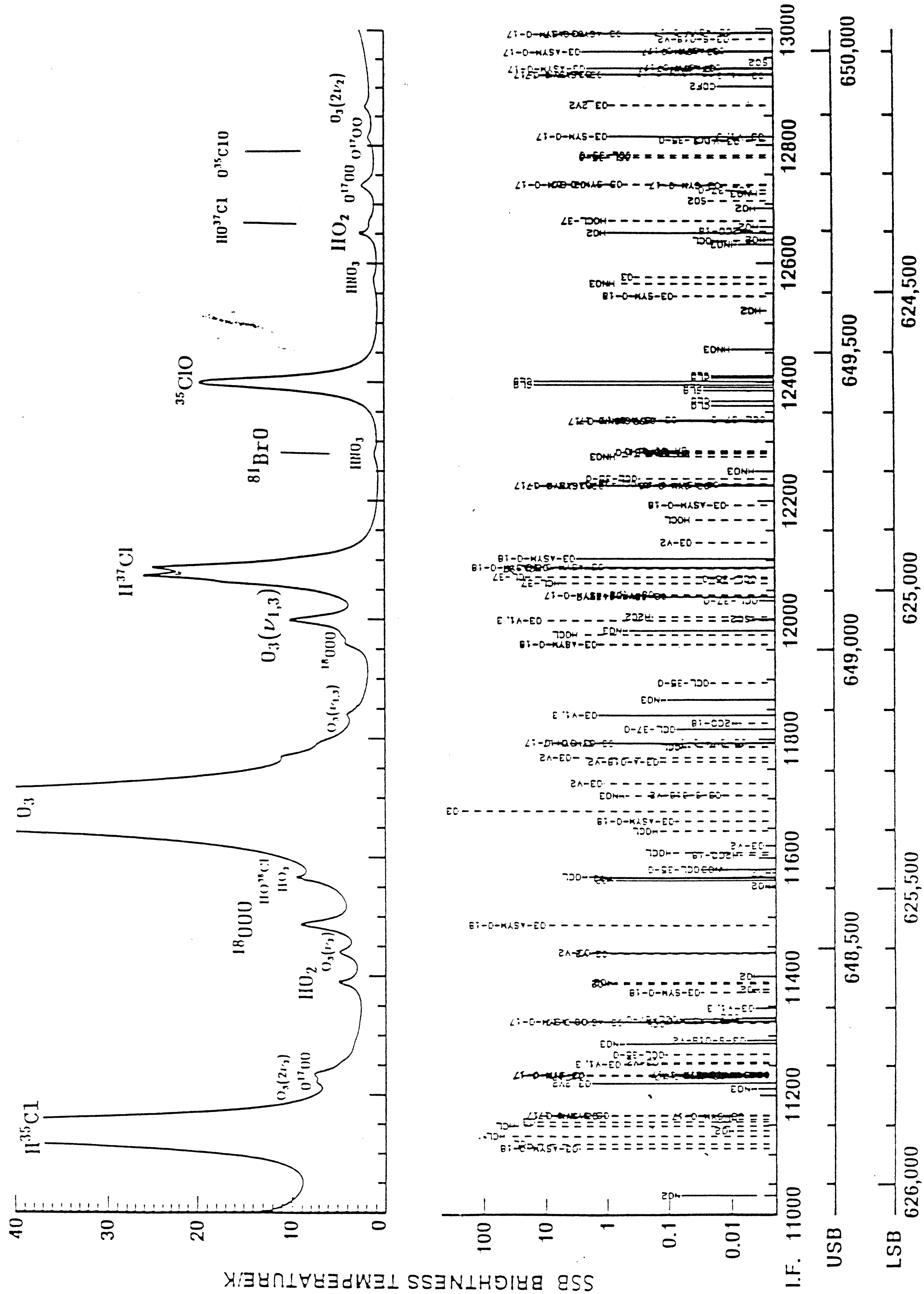
ODD-CHLORINE CHEMISTRY



ODD-HYDROGEN CHEMISTRY



ODD-NITROGEN CHEMISTRY


SSB BRIGHTNESS TEMPERATURE/K
I.F.
USB
LSB
11000
11200
11400
11600
11800
12000
12200
12400
12600
12800
13000
648,500
649,000
649,500
650,000
626,000
625,500
625,000
624,500
$H^{35}Cl$
$H^{37}Cl$
O_3
^{35}ClO
^{81}BrO
HO_2
HNO_3
^{18}OOO
$O_3(\nu_{1,3})$
$O_3(2\nu_2)$
$O^{17}OO$
$HO^{37}Cl$
$O^{35}ClO$

GLOBAL CHANGE TECHNOLOGY: STRATOSPHERIC OZONE DEPLETION

The 550-650 GHz SPECTRAL REGION

- This is the *only* spectral region which allows *simultaneous* measurement of ClO and HCl at all times of day and night
  - ClO is the key molecule by which chlorine destroys stratospheric ozone
  - HCl is the key molecule by which chlorine is removed from the stratosphere
  - Simultaneous measurements of ClO and HCl are needed on a global scale at all times of day and night
    - * Abnormally large values of ClO and small values of HCl led to the antarctic 'ozone hole' — *this may be occuring elsewhere*
- Many additional molecules important for a more complete understanding of ozone depletion can also be simultaneously measured
  - Ozone itself, and all its isotopes: O_3, ^{18}OOO, $O^{18}OO$, ^{17}OOO, $O^{17}OO$
  - Chlorine/bromine destruction cycles: HOCl, OClO, CH_3Cl, BrO
  - Hydrogen destruction cycle: HO_2, H_2O, H_2O_2
  - Nitrogen destruction cycle: NO_2, NO, N_2O, HNO_3
  - Others: temperature, pressure, CO, H_2CO, HCN, SO_2, O_2

JWW's file GCT600.TEX: UNIQ600.TEX (TEX'd February 15, 1989)

GLOBAL CHANGE TECHNOLOGY: STRATOSPHERIC OZONE DEPLETION

550–650 GHz TECHNOLOGY NEEDS

- Need low-noise radiometers operating at ~30–80 K temperature
  - Radiometer noise is given by $\frac{T_{sys}}{\sqrt{(\Delta\nu)(\Delta t)}}$
    - * $\Delta\nu$ is required spectral resolution (~0.3–30 MHz), set by atmospheric line widths
    - * Δt is allowed integration time (~1 s), set by satellite motion
    - * T_{sys} is system 'noise temperature', set by technology
  - The only means available to get low noise is through new technology for low T_{sys}
    - * Need: $T_{sys} \leq 3000$ K
    - * Current technology: $T_{sys} \geq 6000$ K
  - The following 550–650 GHz technology is needed for low T_{sys}
    - * Radiometer architecture to minimize noise
    - * Low-noise non-linear device (mixer) for frequency-conversion
    - * Local oscillators with ~1 mW power
    - * Low-loss method for combining signal and local oscillator
    - * Low-loss method for matching ~2–20 GHz mixer output to first stage amplifier

ASTROPHYSICS-INTERSTELLAR MEDIUM

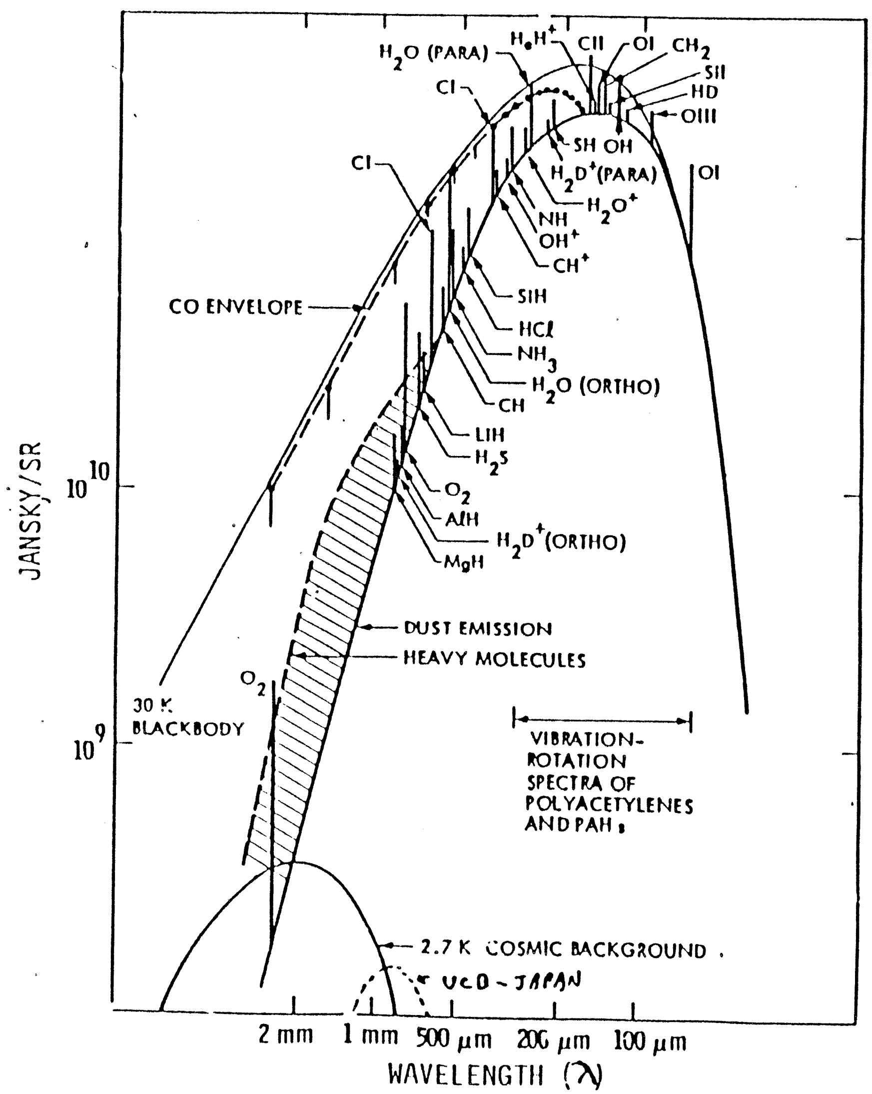
1 mm = 300 GHZ = 15K

- "BLACKBODY" RADIATION FROM DUST
  - DIRECT DETECTORS WITH MODERATE RESOLUTION
- SHARP SPECTRAL LINES FROM ROTATION STATES OF STAR-FORMING SPECIES
  - HETERODYNE DETECTORS
    - IDENTIFY SPECIES
    - DEVIATIONS FROM LABORATORY SPECTRA GIVES DOPPLER SHIFT (DYNAMICS OF MOLECULAR CLOUD)
    - WEAK SIGNALS REQUIRES HIGH SENSITIVITY $\Rightarrow$ SUPERCONDUCTIVITY MIXERS

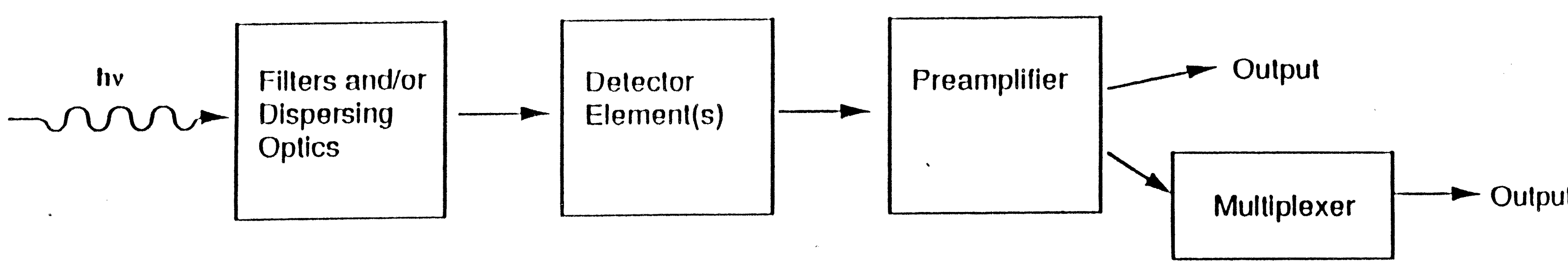
JPL

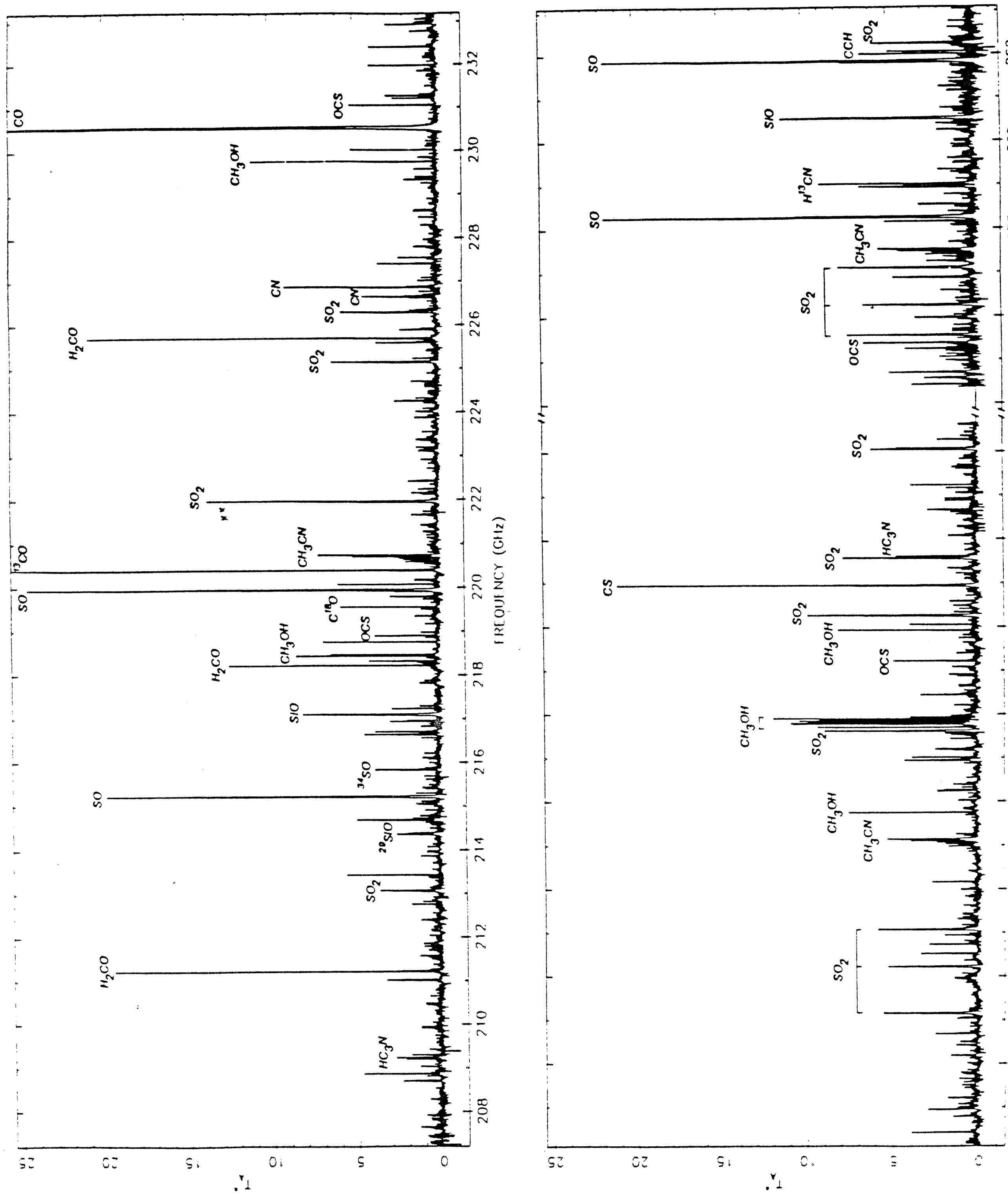
SUBMILLIMETER SCIENCE

ANTICIPATED SPECTRUM OF STAR-FORMING CLOUD

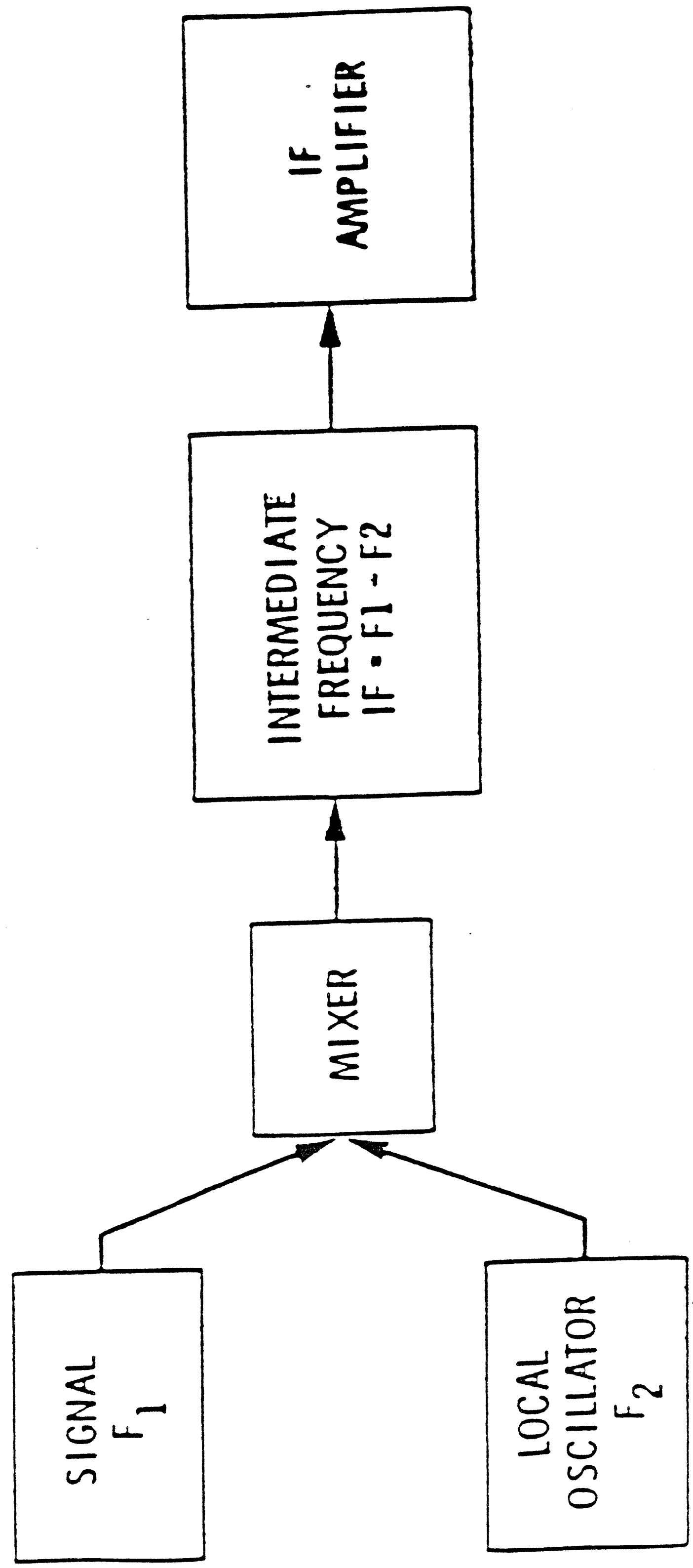


DIRECT DETECTOR SYSTEMS
CONCEPTUAL INSTRUMENT DESIGN



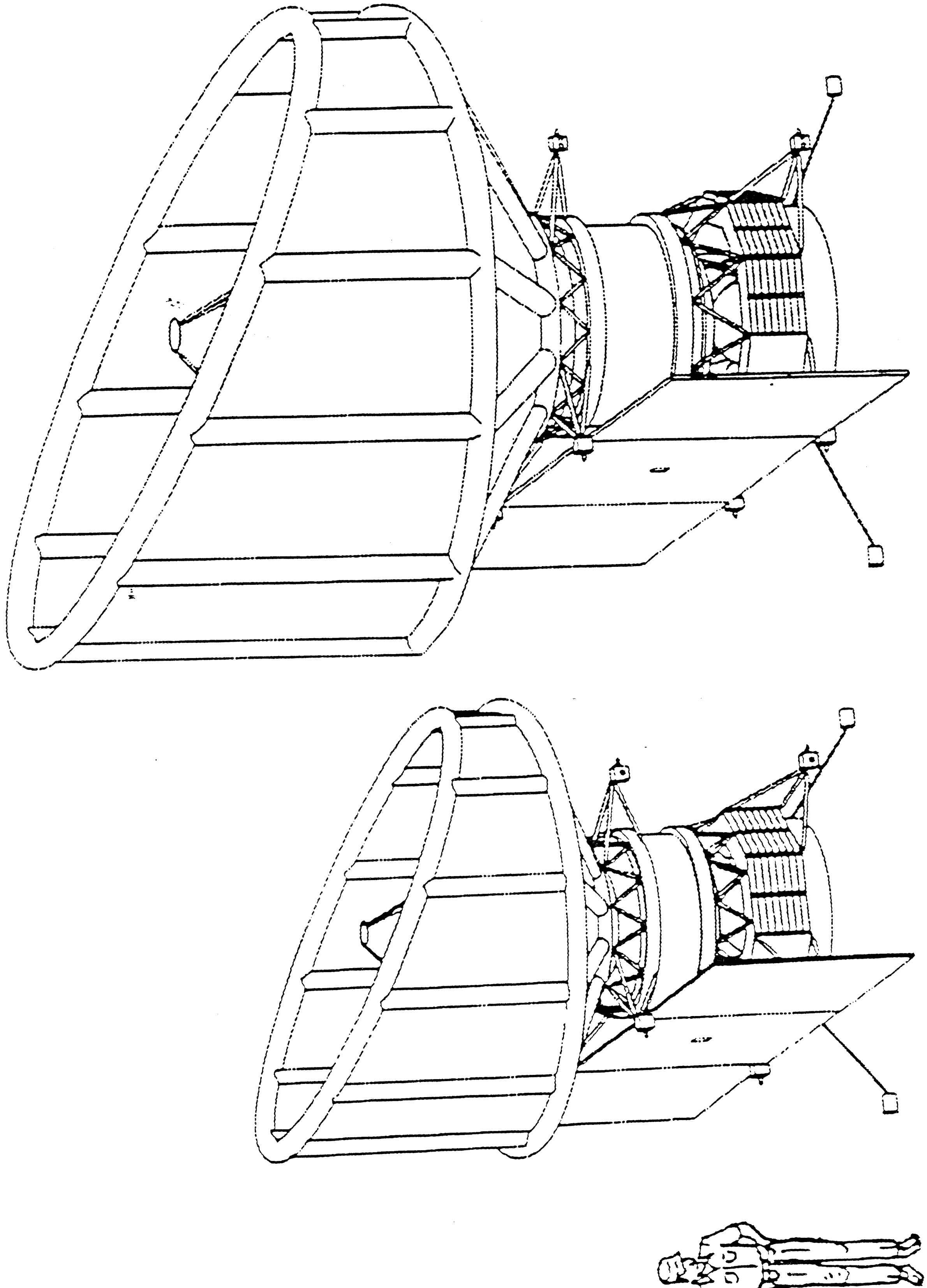

CO
OCS
CH3OH
CN
SO2
H2CO
SO2
CH3CN
SO
OCS
CH3OH
H2CO
SIO
SO
SO2
H2CO
HC3N
FREQUENCY (GHz)
SO
CCH
SO2
SIO
SO
CH3CN
SO2
OCS
SO2
SO2
HC3N
CS
SO2
CH3OH
OCS
CH3OH
SO2
CH3OH
CH3CN
SO2

HETERODYNE RECEIVER TECHNOLOGY



CANDIDATE SUBMILLIMETER APPLICATIONS/MISSIONS

- 10m SUBMM TELESCOPE ON HAWAII
  - AT 14,000 ft.
  - LIMITED TO ATMOSPHERIC "WINDOWS"
- KUIPER AIRBORNE OBSERVATORY
  - 1m TELESCOPE
- BALLOONS
- SPACECRAFT
  - UPPER ATMOSPHERIC RESEARCH SATELLITE, 1991
  - SUBMM WAVE ASTRONOMY SATELLITE, 1994
  - SUBMILLIMETER EXPLORER, 1998?
  - SUBMM IMAGING LINE SURVEY, 1999?
  - EOS-B MILLIMETER WAVE LIMB SOUNDER, 1999?
  - LARGE DEPLOYABLE REFLECTOR, 2004?
- LUNAR-BASED INTERFEROMETER, 2007?

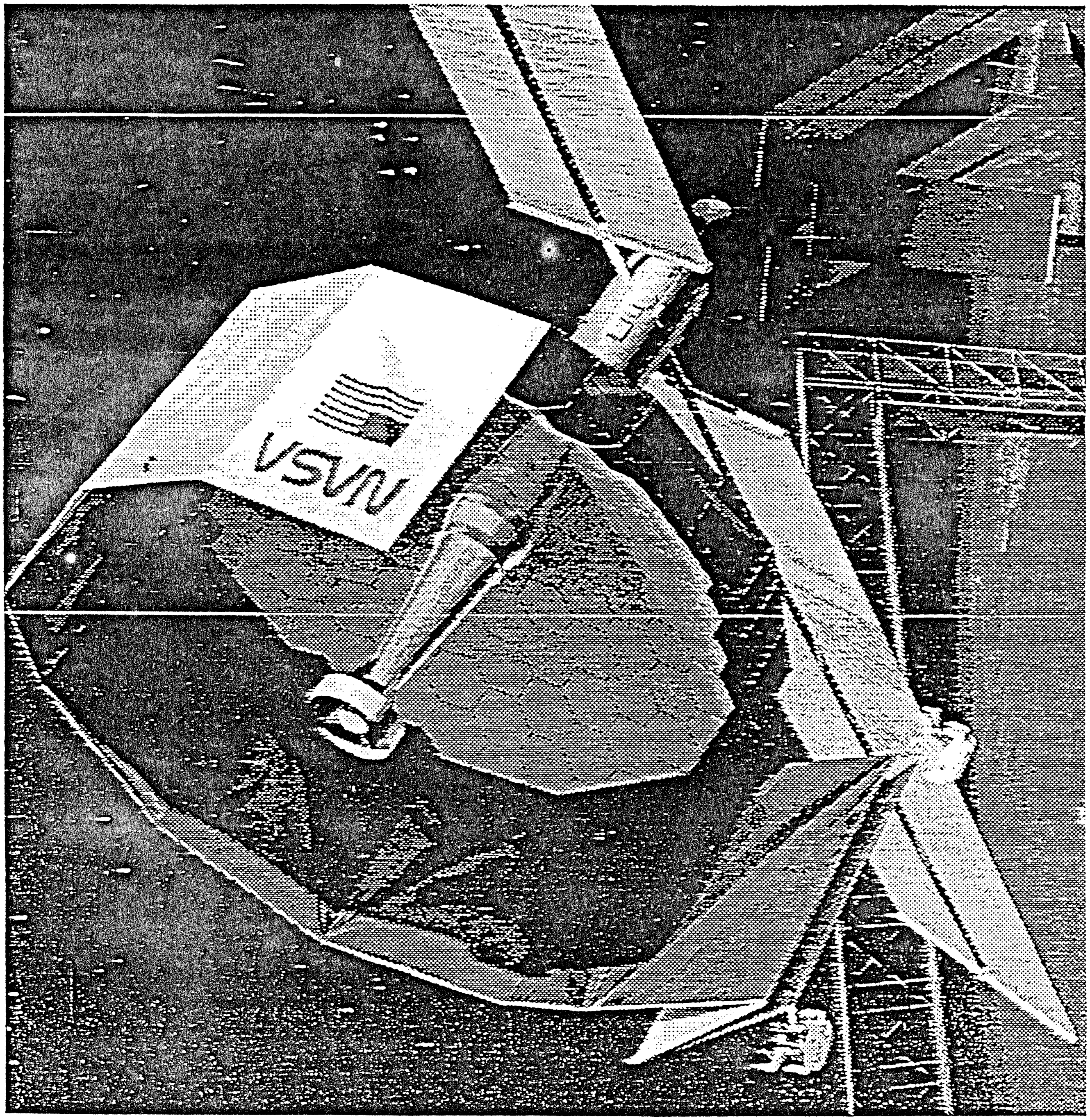


SUBMILLIMETER MODERATE MISSION (SMMM)

SUBMILLIMETER - INFRARED LINE SURVEY (SMILS)

EXPLORER (SMME)

THE LARGE DEPLOYABLE REFLECTOR



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SUBMILLIMETER APERTURE SYNTHESIS ARRAY

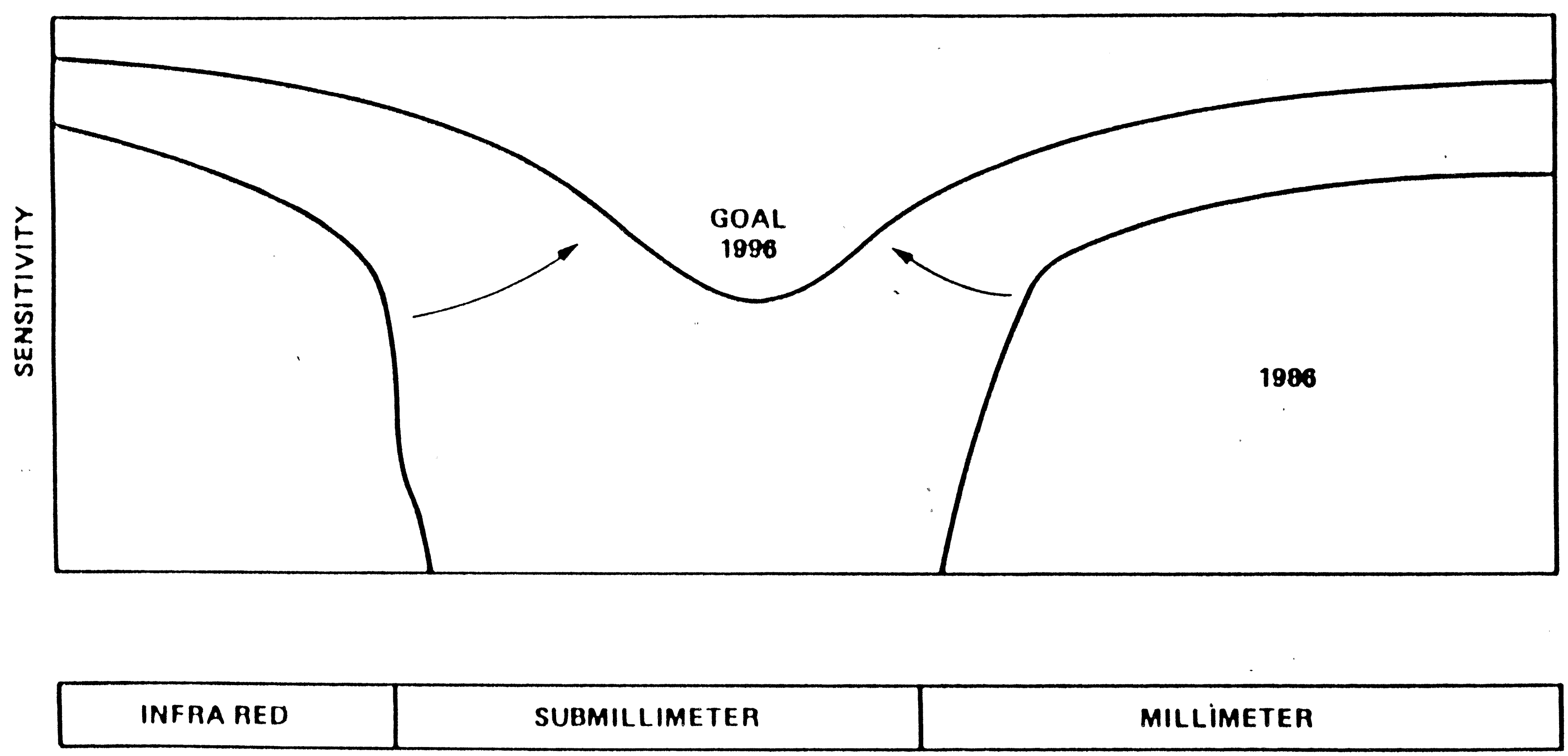
TECHNOLOGY PROGRAM GOALS FOR SUBMILLIMETER MISSIONS

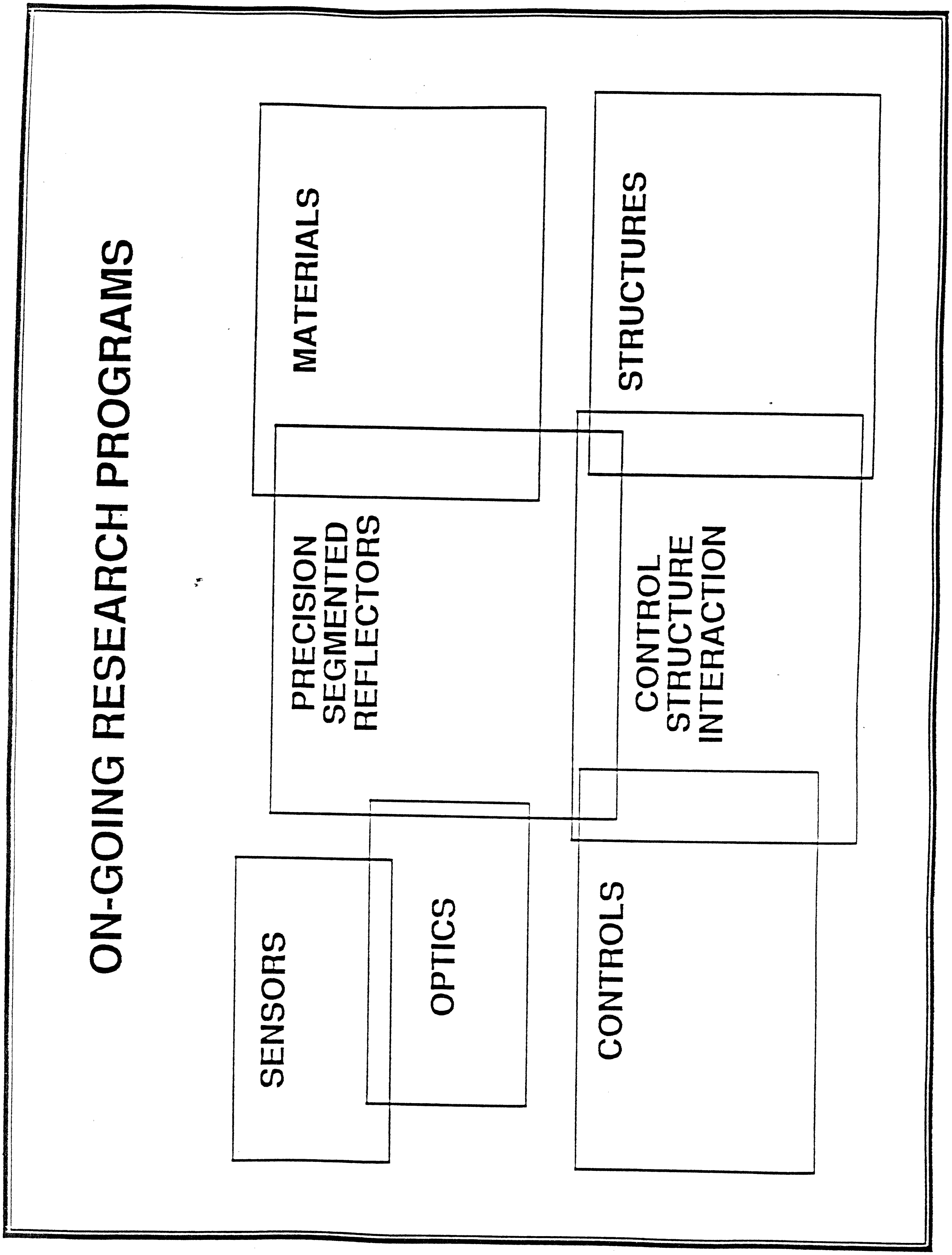
- PROVIDE THE ENABLING TECHNOLOGIES FOR SUBMILLIMETER SPACE ASTRONOMY
- BALANCE THE PACE OF DEVELOPMENT TO MATCH SUBMILLIMETER MISSION SCHEDULES
- ADVANCE THE MATURITY TO A LEVEL OF READINESS APPROPRIATE FOR MISSION BASELINE DESIGN

NASA OAST

COHERENT SENSOR RESEARCH

NEED FOR SUBMILLIMETER COHERENT SENSORS




ON-GOING RESEARCH PROGRAMS
SENSORS
OPTICS
CONTROLS
PRECISION
SEGMENTED
REFLECTORS
CONTROL
STRUCTURE
INTERACTION
MATERIALS
STRUCTURES

TECHNOLOGY DOMAINS

INSTRUMENT TECHNOLOGIES

- HETERODYNE SYSTEM
- DIRECT DETECTOR SYSTEM
- CRYOGENICS

TELESCOPE TECHNOLOGIES

- PANELS / MATERIALS
- STRUCTURES
- FIGURE SENSING & CONTROL
- OPTICAL SYSTEM

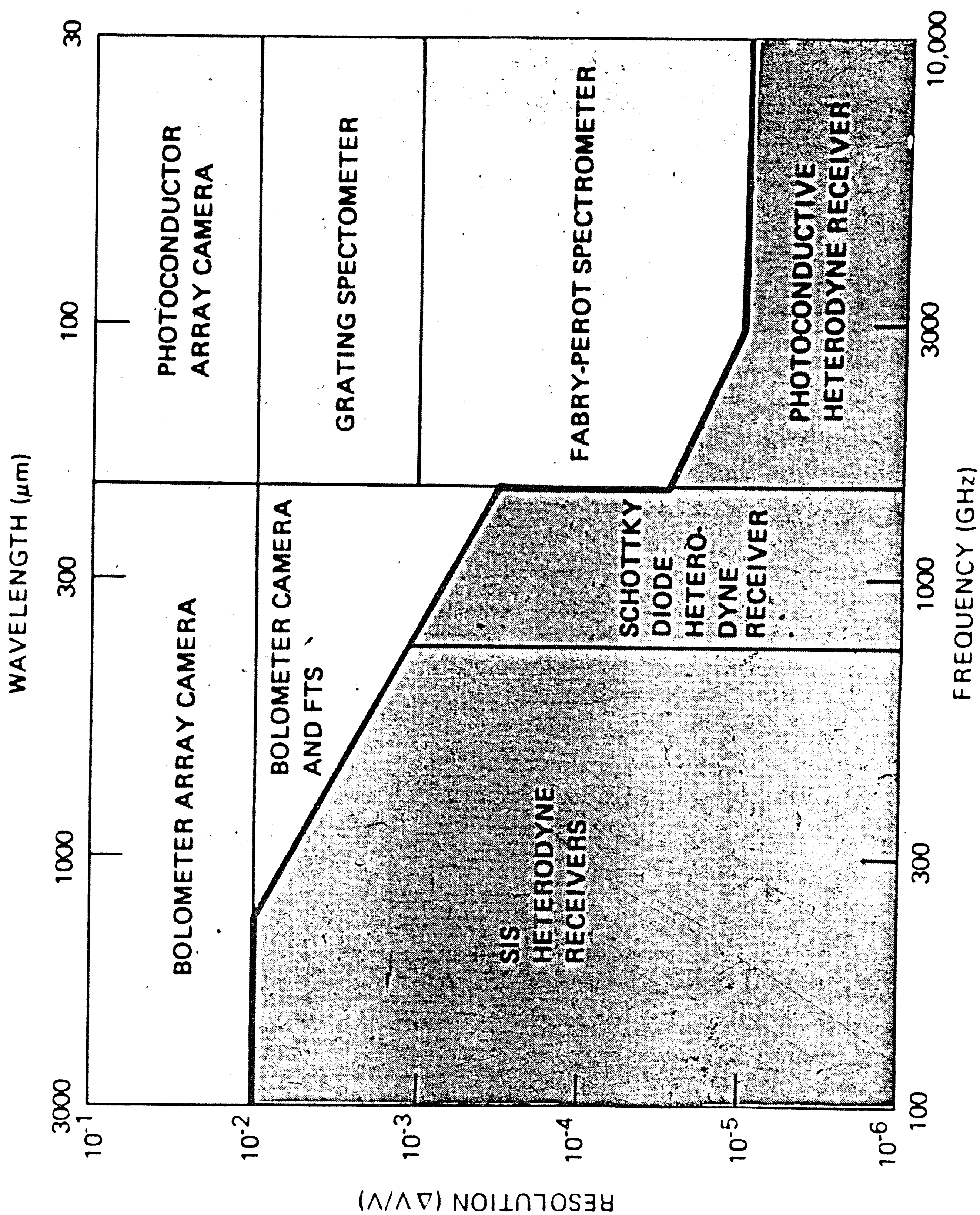
SPACECRAFT TECHNOLOGIES

- POWER & THERMAL
- PROPULSION
- COMMUNICATIONS
- COMPUTING & DATA
- POINTING

SUPPORTING TECHNOLOGIES

- LAUNCH SYSTEMS
- IN-SPACE ASSEMBLY & SERVICE
- MISSION OPERATIONS

SUBMILLIMETER HETERODYNE SENSORS
LDR INSTRUMENTS



SUBMILLIMETER WAVE SENSOR TECHNOLOGY

JPL QUANTUM WELL MULTIPLIER LOCAL OSCILLATOR OAST

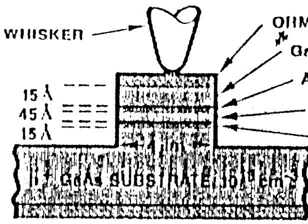
TECHNICAL GOAL

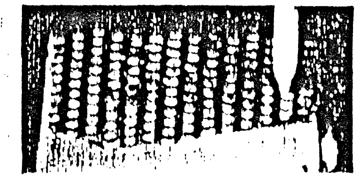
— LOCAL OSCILLATOR SOURCE	300-1500 GHz
— OUTPUT POWER	1 μW-1mW
— TUNEABILITY	10-20%
— LINEWIDTH	$1:10^8$
— FREQUENCY STABLE	$1:10^8$
— SPACE QUALIFIABLE	

TECHNICAL APPROACH

— SOLID STATE SOURCE — QUANTUM WELL BASED DEVICE	
— FUNDAMENTAL OSCILLATOR	300-600 GHz
— HARMONIC GENERATOR	600-1500 GHz

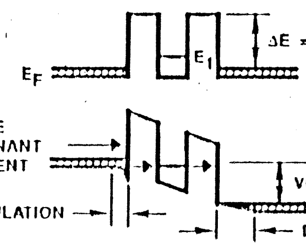
QUANTUM WELL DEVICES

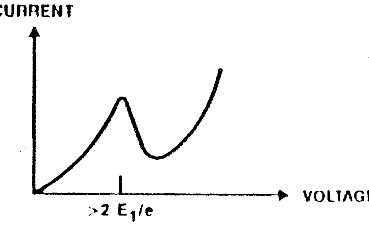




SEM OF DEVICE CHIP MOUNTED IN WAVEGUIDE

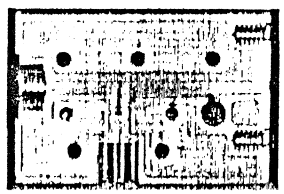
PRINCIPLE OF OPERATION

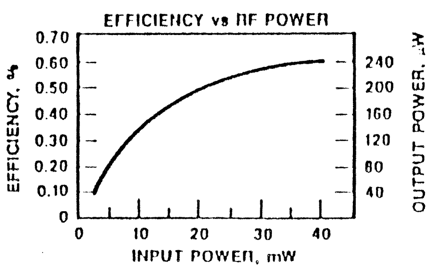




SUBMILLIMETER WAVE MULTIPLIERS

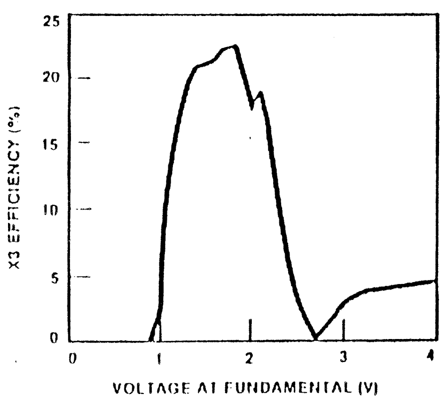
WAVEGUIDE MOUNT



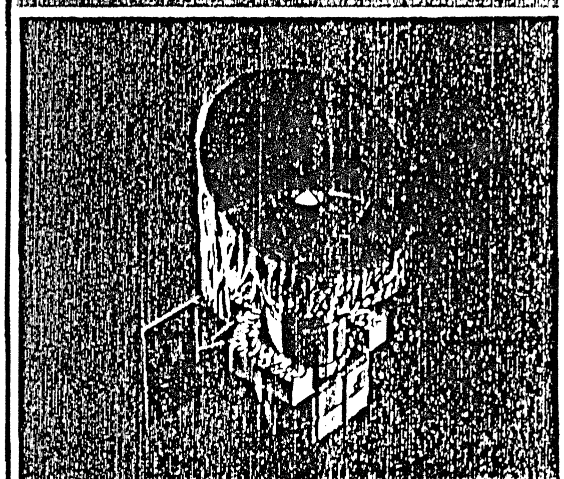


200 GHz TRIPLER PERFORMANCE

THEORETICAL ANALYSIS



- NEGATIVE RESISTANCE GIVES HIGH EFFICIENCY
- SYMMETRY YIELDS ONLY ODD HARMONICS



SUBMILLIMETER WAVE SENSOR TECHNOLOGY

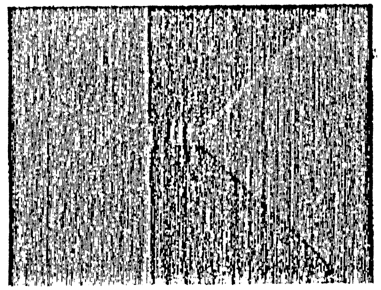
JPL SIS MIXERS AND ARRAYS OAST

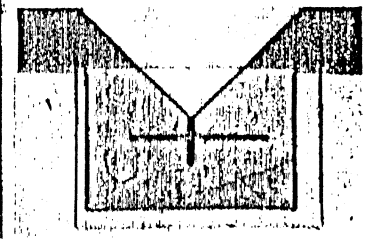
- SINGLE ELEMENT MIXERS 600-1500 GHz
- MIXER ARRAYS UP TO 5x5
- SENSITIVITY 10 x QUANTUM LIMIT
- BANDWIDTH 10-20%
- TUNEABILITY
- SPACE QUALIFIABLE

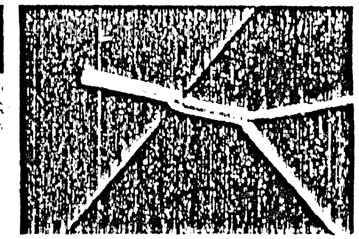
TECHNICAL APPROACH

- SIS JUNCTIONS
- REFRACTORY MATERIAL — NbN/MgO/NbN
- PLANAR ANTENNAS
- PLANAR ANTENNA ARRAYS

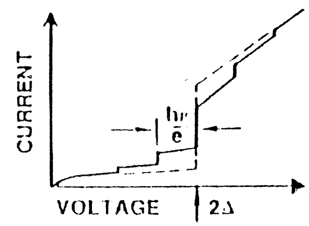
NbN/MgO/NbN SIS DEVICES


SINGLE MESA SIS JUNCTION

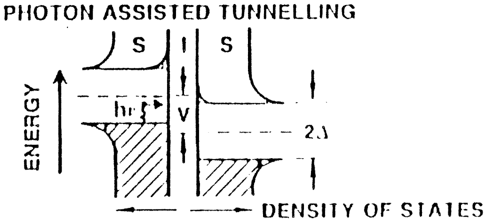

EDGE TUNNEL JUNCTION


CROSSLINE TUNNEL JUNCTION

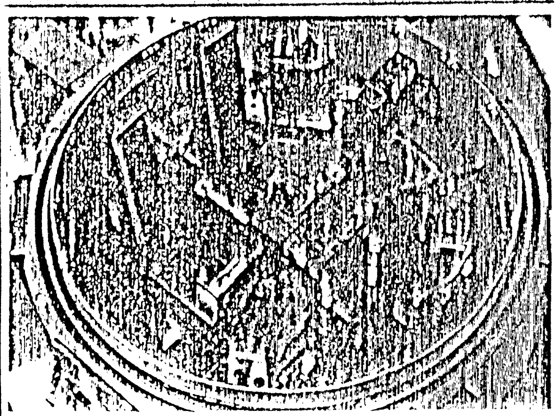
PRINCIPLE OF OPERATION

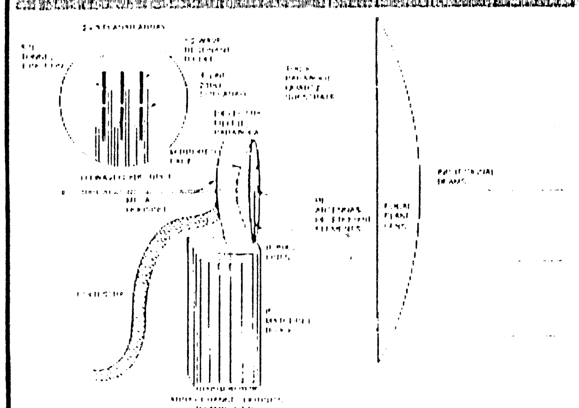


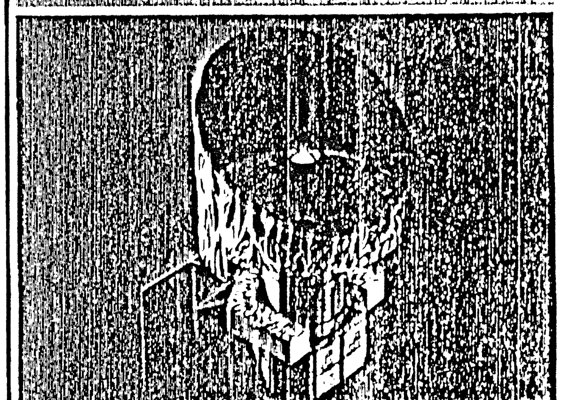
PHOTON ASSISTED TUNNELLING



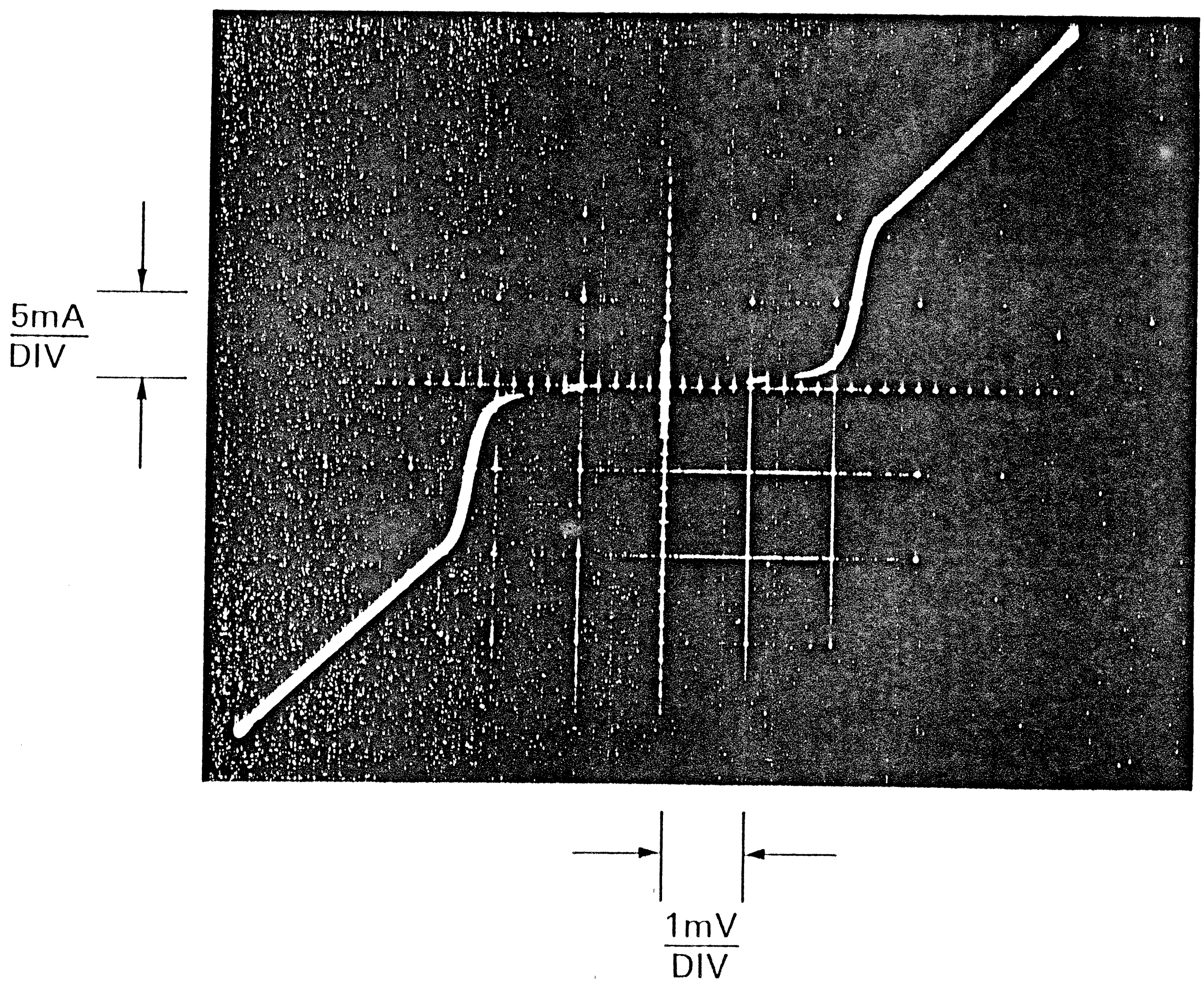
TEST FACILITY



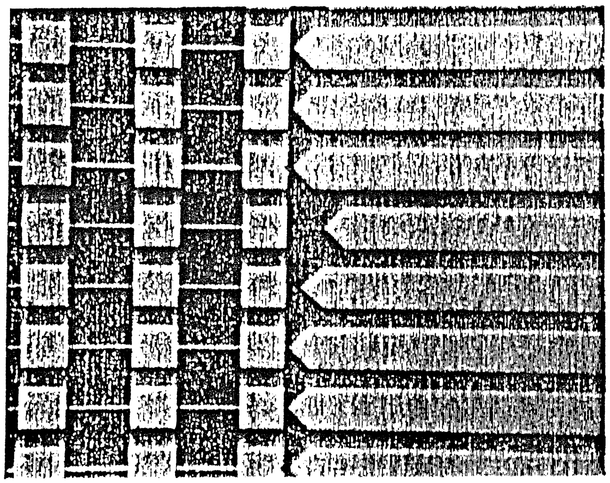




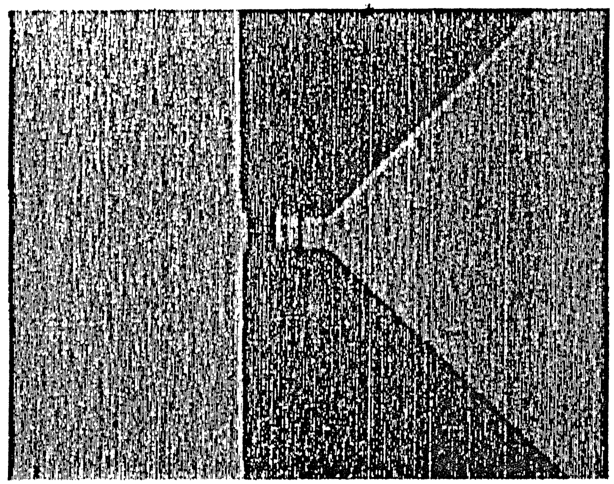
CURRENT-VOLTAGE CHARACTERISTICS OF NbN/MgO/NbN TUNNEL JUNCTIONS



NbN/MgO/NbN SIS Tunnel Junction Geometries



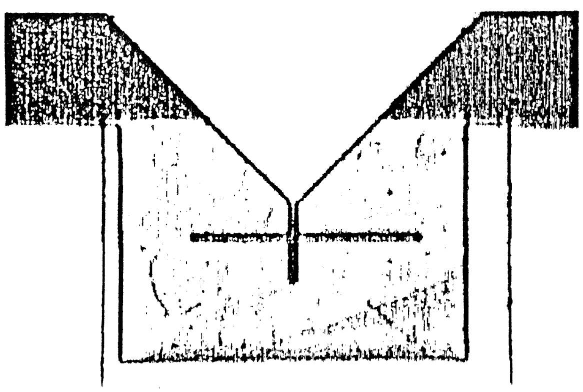
SIS Junction Integrated with Antenna and Filter



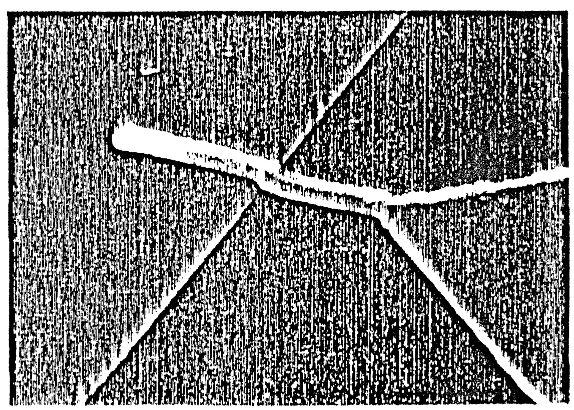
Single Mesa SIS Junction

Mesa Junction Characteristics

Areas	$1 \mu m^2$
E_g	4.5 meV
J_c	$10\ kA/cm^2$
R	$20\ \Omega$
$\omega RC(200)$	3



Crossline Tunnel Junction



Edge Tunnel Junction

Characteristics

	Cross	Edge
Area(μm^2)	1	0.1
E_g(meV)	5	5
J_c(kA/cm^2)	10	15
R(Ω)	20	150
$\omega RC(200)$	3	2

HIGH TEMPERATURE SUPERCONDUCTIVITY

- PRESENT SIS MIXERS OPERATE BELOW 10K WHICH REQUIRES LIQUID HELIUM COOLANT

- HIGH TC DEVICES HOLD THE PROMISE OF OPERATION AT TEMPERATURES ABOVE 60K WHICH CAN BE ACHIEVED WITH STIRLING COOLERS

JPL

HIGH T_c SUPERCONDUCTING MATERIAL PROPERTIES

	PRESENT S.O.A. TECHNOLOGY	NEAR-TERM TECHNOLOGY	FUTURE TECHNOLOGY BaYCuO
1. MATERIAL	LEAD BASED ALLOYS E.G. PB-IN-AU	NIOBIUM NITRIDE	
2. SUPERCONDUCTING TRANSITION TEMPERATURE (T_C)	6-7°K	16-17°K	94°K
3. SUPERCONDUCTING GAP (2Δ)	2.6 MEV	5.6 MEV	24 MEV
4. UPPER OPERATING FREQUENCY LIMIT	600 GHz	1500 GHz	6000 GHz
5. STABILITY ON THERMAL CYCLING	POOR	EXCELLENT	?
6. MECHANICAL PROPERTIES	SOFT	REFRACTORY, ROBUST	?

SUMMARY

- NASA HAS MANY SCIENTIFIC APPLICATIONS FOR TERAHERTZ INSTRUMENTS
  - 300 GHz TO 3 THz
- ESA ALSO HAS SUBMM APPLICATIONS
- THE TECHNOLOGY FOR THESE MISSIONS IS CHALLENGING AND UNDER DEVELOPMENT