HAMSR – The High Altitude MMIC Sounding Radiometer

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Abstract- **HAMSR is a millimeter wave atmospheric temperature and humidity sounder that utilizes state of the art technology to enable substantial reductions in size and mass while at the same time achieve improved measurement sensitivity and accuracy. It is the first such instrument to use receivers based entirely on newly developed monolithic microwave integrated circuit technology. Sponsored by the NASA Instrument Incubator Program, HAMSR has been under development for the past 2 1/2 years. The first science mission takes place in Florida this summer, where HAMSR is deployed on the NASA ER-2 during the CAMEX-4 hurricane field campaign and will provide core atmospheric soundings to a number of investigators. HAMSR represents the next generation of microwave sounders.**

I. Background

A. *Overview*

The High Altitude MMIC Sounding Radiometer – HAMSR – was built by the Jet Propulsion Laboratory (JPL) to demonstrate and validate new miniature technology and advanced design concepts. It is the world's first atmospheric sounder to use receivers based on monolithic microwave integrated circuits (MMICs). HAMSR is intended to demonstrate new concepts developed for the next generation of sounders, to be used on the future National Polar-orbiting Operational Satellite System (NPOESS).

HAMSR is built around a core of miniaturization technology developed under the short-lived Integrated Multispectral Atmospheric Sounder (IMAS) program, and it uses a flexible design that makes it easily reconfigurable. This makes it ideally suited as a testbed for new components. It also implements dual-band temperature sounding, which results in greater retrieval accuracy as well as a broader measurement scope. HAMSR is the first aircraft microwave sounder with both temperature and humidity sounding capabilities in a single package. Due to miniaturization, this instrument can be accommodated on even small platforms, such as unmanned aerial vehicles (UAVs).

HAMSR is one of the first complete instrument developments coming out of the Instrument Incubator Program (IIP), launched by NASA's Earth Science Technology Office (ESTO) in 1998. From a start in January 1999, HAMSR was essentially completed in early 2000 as a laboratory instrument suitable for ground based applications. It has since been upgraded for deployment on NASA's high altitude ER-2 aircraft. The first test flights were successfully carried out in July 2001, and HAMSR will participate in the fourth NASA Convection and Moisture Experiment (CAMEX-4) in Florida this summer. HAMSR will be used in the future as a testbed to validate new technology as well as to support scientific missions.

B. *Programmatic Context*

HAMSR is essentially an implementation of the microwave portion of IMAS, and uses technology and components developed under that program. IMAS – a combined infrared and microwave sounder – was planned as a follow-on to the Atmospheric Infrared Sounder (soon to be launched). It was carried through Phase B and was cancelled in 1998, but not before key technology components had been developed. In the millimeter wave area these included prototype MMIC receivers and compact solid state filter banks.

Although the IMAS effort was eventually cancelled, it sponsored numerous developments in technology and advanced designs that will greatly benefit others in the future. Already, two microwave systems (in addition to HAMSR) have been derived from the IMAS effort. An example is the Advanced Technology Microwave Sounder (ATMS), under development for the NPOESS Preparatory Project (NPP). It is, as was IMAS, ultimately intended for NPOESS.

II. Science and Measurements

A. *Measurement Concept*

Sounding is based on the fact that the thermal radiation received by a radiometer originates at wavelength-dependent depths in the atmosphere. This is caused by a non-uniform absorption spectrum, particularly absorption lines. Thus, at wavelengths near the peak of a line, absorption may be so strong that most of the underlying atmosphere is opaque, and only the top of the atmosphere is "seen". Conversely, at wavelengths far away from the lines, the atmosphere may be nearly transparent, and the bottom of the atmosphere or the surface is seen. Through spectral analysis, i.e. by measuring narrow spectral bands or "channels", it is then possible to probe into different depths of the atmosphere. A "weighting function" expresses which portion of a channel's signal originates from different depths. For a radiometer looking down into the atmosphere, a typical weighting function reaches a peak at a certain depth, which is characteristic for that channel. A set of channels is selected so that the respective weighting functions are evenly distributed through the atmosphere.

HAMSR has a number of oxygen channels (at 50-60 and 118 GHz) and water vapor channels (at 183 GHz). Since the vertical distribution of oxygen is stable and known, the oxygen channels allow the temperature distribution to be determined. With that known, the H_2O channels allow the vertical distribution of water vapor density to be determined. The distribution of liquid water can also be derived. Fig. 1 shows the microwave absorption spectrum for oxygen, water vapor and liquid water, and Fig. 2 shows the HAMSR weighting functions.

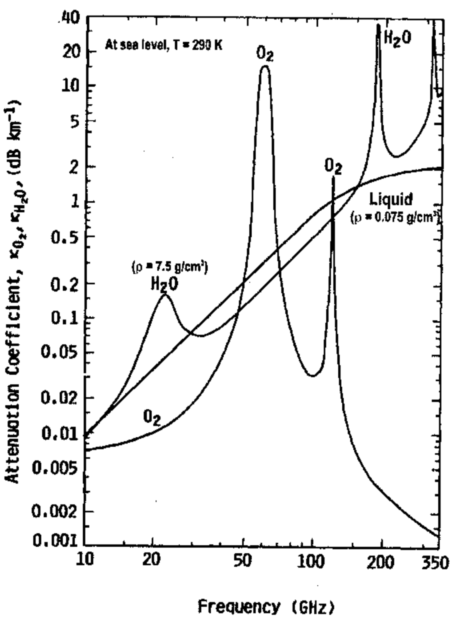

Fig. 1. Microwave absorption spectrum

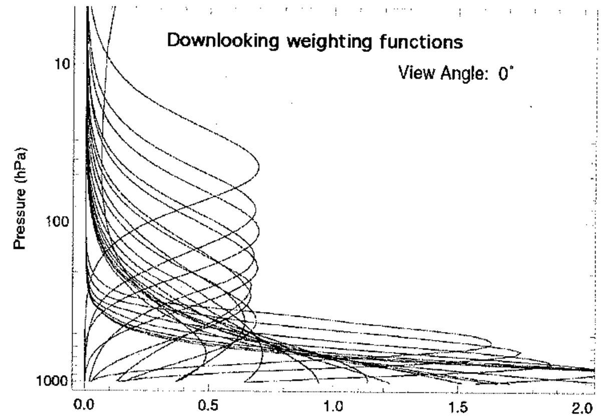

Fig. 2. HAMSR down-looking weighting functions for nadir

B. *Measurement Requirements*

The HAMSR radiometric and spectral measurement requirements are identical to those of IMAS, which were based on the need to provide soundings of the troposphere in the presence of clouds. The microwave observations are used to "cloud clear" the infrared observations, i.e. enable inferring clear-sky infrared radiances from the cloudy-sky measurements. The cloud-cleared radiances are then used to retrieve atmospheric profiles. With this approach there is no need for microwave soundings above the clouds, and therefore both IMAS and HAMSR lack most of the stratospheric and mesospheric channels that AMSU (and ATMS) has. The IMAS

TABLE I
HAMSR MEASUREMENT SPECIFICATIONS

Chan #	Wt-func. Peak [mb or mm] [a]	Center Freq. [GHz]	Offset [GHz]	Channel Center Freq. [GHz] [b]	LO Freq. [GHz]	IF Freq. [GHz]	Bandwidth [MHz]	Noise Fig. [dB]	NEDT [K] [c]
I-1	Sfc/[30 mm]	118.75	-5.5	113.25	124	10.75	1000	8	0.31
I-2	Surface	"	-3.5	115.25	124	8.75	1000	8	0.31
I-3	Surface	"	-2.55	116.2	124	7.8	500	8	0.44
I-4	1000 mb	"	-2.05	116.7	124	7.3	500	8	0.44
I-5	750 mb	"	-1.6	117.15	124	6.85	400	8	0.50
I-6	400 mb	"	-1.2	117.55	124	6.05	400	8	0.50
I-7	250 mb	"	±0.800	117.95 & 119.55	124	4.45 & 6.45	2x400	8	0.35
I-8	150 mb	"	±0.450	118.3 & 119.2	124	4.8 & 5.7	2x300	8	0.40
I-9	80 mb	"	±0.235	118.515 & 118.985	124	5.015 & 5.485	2x130	8	0.61
I-10	40 mb	"	±0.120	118.63 & 118.87	124	5.13 & 5.37	2x100	8	0.70
II-1	Sfc/[100 mm]	50.3	0	**50.3**	46	4.3	340	5	0.22
II-2	Surface	51.76	0	51.76	46	5.76	400	5	0.20
II-3	1000 mb	52.8	0	**52.8**	46	6.8	400	5	0.20
II-4	750 mb	53.596	±0.115	**53.481 & 53.711**	46	7.711 & 7.481	2x170	5	0.22
II-5	400 mb	54.4	0	**54.4**	46	8.4	400	5	0.20
II-6	250 mb	54.94	0	**54.94**	46	8.94	400	5	0.20
II-7	150 mb	55.5	0	**55.5**	46	9.5	330	5	0.22
II-8	90 mb	56.02 & 56.67	0	56.02 & 56.67	46	10.67 & 10.02	270 & 330	5	0.16
III-1	[11 mm]	183.31	-17.31	166	166	1 (0.01 -2)	2x2000	8.3	0.17
III-2	[6.8 mm]	"	±10.0	173.31 & 193.31	183.31	10	2x3000	8.3	0.14
III-3	[4.2 mm]	"	±7.0	**176.31 & 190.31**	183.31	7	2x2000	8.3	0.17
III-4	[2.4 mm]	"	±4.5	178.81 & 187.81	183.31	4.5	2x2000	8.3	0.17
III-5	[1.2 mm]	"	±3.0	**180.31 & 186.31**	183.31	3	2x1000	8.3	0.24
III-6	[0.6 mm]	"	±1.8	181.51 & 185.11	183.31	1.8	2x1000	8.3	0.24
III-7	[0.3 mm]	"	±1.0	**182.31 & 184.31**	183.31	1	2x500	8.3	0.34

[a] Numbers in brackets pertain to water vapor weighting functions in terms of burden and apply to a 60° view angle; others pertain to temperature weighting functions in terms of pressure and apply to a nadir view
[b] Numbers in bold indicate channels that are identical to AMSU channels
[c] NEDT values are for 25-ms integration times

measurement accuracy was intended to exceed that of AMSU, and HAMSR reflects that. Furthermore, in an aircraft or ground deployment the available integration time is much greater than in a space deployment, so that the measurement accuracy of HAMSR will normally exceed that of an equivalent satellite instrument by a substantial margin. HAMSR is therefore a very sensitive and accurate radiometer that is well suited for validation purposes.

The HAMSR channel set is identical to the IMAS set and is a superset of the tropospheric AMSU channels. Table I lists the spectral and other characteristics of HAMSR, including the radiometric sensitivity ("noise-equivalent delta-temperature" – NEDT) for each channel. Channels that are identical to AMSU channels are highlighted. The table also indicates where each channel's weighting function peaks. As specified for IMAS, HAMSR implements dual-band temperature sounding and single-band humidity sounding. The 118-GHz band was intended to be the primary temperature sounding band, while the 53-GHz band was intended as a backup for highly opaque conditions and to provide science continuity for climate studies. A subset of the 118-GHz channels maps directly onto the 53-GHz channels, with identical weighting functions (for a standard atmosphere). HAMSR, as will ATMS, has additional 183-GHz channels (over AMSU), which yields higher water vapor sounding resolution.

With these performance specifications, along with an estimated calibration accuracy of better than 0.5 K, a temperature profile accuracy of better than 2 K in 2-3 km layers and a water profile accuracy of better than 15-20% in 3-4 km layers are achievable. Liquid water profile accuracy is expected to exceed 40% in 4 km layers.

III. The Instrument

A. System Design

A block diagram of the instrument is shown in Fig. 3 and a photograph of the sensor part of the instrument is shown in Fig. 4. The incoming radiation, from the atmosphere or from internal calibration sources, is received by two scanning reflectors and diplexed into three frequency bands by a quasi-optics system which directs the signals into feed horns at the inputs of the radiometers, each of which consists of a heterodyne receiver. The intermediate-frequency (IF) signals are

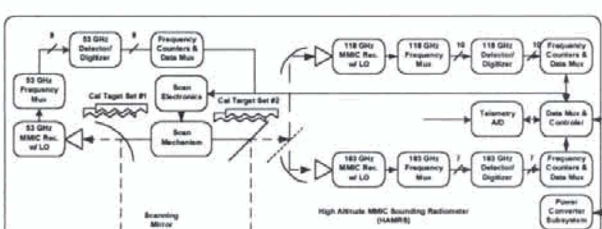

Fig. 3. HAMSR block diagram

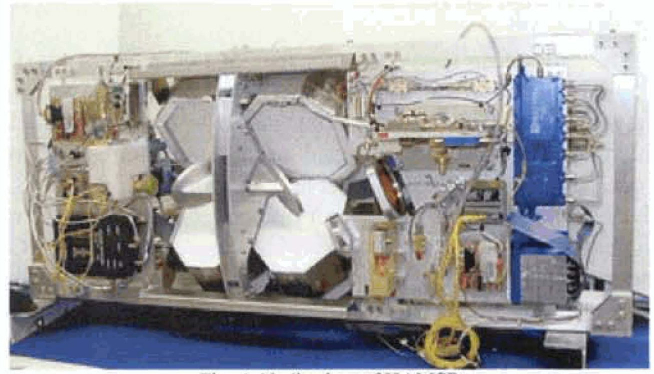

Fig. 4. Nadir view of HAMSR

fed to frequency multiplexers, which separate out the spectral channels and in turn feed power detectors followed by digitizers. The results are read by a digital data system after fixed (but programmable) integration intervals and stored on a compact-flash card. Another section feeds thermistor signals to analog-to-digital converters, which are also read by the controller. During aircraft operations the data system also reads and stores a navigation data stream provided by the aircraft.

B. Optical Subsystem

A layout of the HAMSR optics subsystem is shown in Fig. 5. To enable the system to be easily re-configured, a simple and flexible set of optics was designed, but with some sacrifice in compactness, while meeting strict requirements for low cross-polarization coupling and low sidelobes. Of the two reflectors, one is parabolic and receives the 53 GHz signal with a 75 mm projected aperture, and the other is a smaller flat reflector for the 118 and 183 GHz signals. The two highest frequency signals are diplexed by a high-performance dichroic plate, which was designed and fabricated at JPL. The three parabolic reflectors focus the received signals into corrugated feed horns. All reflectors are illuminated with -30 dB edge illumination to assure high beam efficiency. A scan motor, which includes an encoder and is controlled by servo drive electronics controlled by the data system, drives the scanning mirrors, which are mounted at a 45° angle on a common rotation axis. As the reflectors rotate around this axis, the atmosphere below is scanned in a direction perpendicular to the scan axis – which normally lies in the flight direction. The instantaneous field of view (IFOV) is a cone with a 3-dB width of 5.7° for all channels.

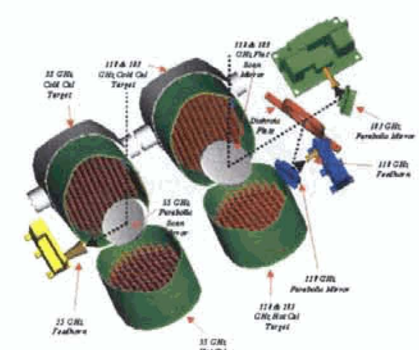

Fig. 5. HAMSR optics subsystem

C. Calibration Subsystem

The calibration subsystem consists of two pairs of blackbody targets, shown in Fig. 5 and visible in Fig. 4 as white octagonal shapes. (The white color is due to foam insulation, which ensures stable and uniform target temperatures.) There is one pair for the 53 GHz band and one for the 118 and 183 GHz bands. Each pair consists of one target at the instrument ambient temperature and one that is heated to about 75° C. The targets were designed and fabricated for HAMSR by Zax. They consist of wedges of absorber material on a metal core, approximately 40 mm long and spaced approximately 10 mm apart. The targets were designed to have less than -50 dB return loss from 40 to 220 GHz, equivalent to an emissivity of better than 0.99999 (although that is degraded somewhat by the insulation). Each contains four thermistors embedded near the tips of selected wedges. Laboratory tests indicate temperature gradients across the targets of less than 0.1° C.

D. Receivers

The 53 and 118 GHz receivers utilize a single-sideband super-heterodyne approach and consist of an InP MMIC low noise amplifier (LNA), cascaded with a microstrip (planar) image reject filter and a mixer which downconverts the signal to an IF frequency of approximately 4–12 GHz. The mixer is a second-harmonic MMIC design on InP. Additional IF gain is provided by MMIC amplifiers. An active MMIC multiplier chain is used to provide a source of local oscillator (LO) power and is driven by a dielectric resonator oscillator (DRO). All modules employ gain compensation to stabilize the gain over the operating temperature range. Fig. 6a is a photograph of the 118-GHz receiver. Both MMIC receivers are IMAS prototypes designed and fabricated by TRW.

When HAMSR was developed, 183-GHz MMIC amplifiers were not yet available – this is still the case – and the 183 GHz band receiver therefore uses a more conventional design. Its front-end is a broadband (12 GHz) double sideband 183 GHz sub-harmonic (x2) mixer using planar Shottky diodes. To cover the wide band from 164 to 195 GHz the receiver operates with switched local oscillators that center the receive band at either 183.31 or 166 GHz. The LO signals are derived, through a x6 frequency multiplier, from two DROs at 13.8 and 15.3 GHz. The 183-GHz receiver was built by Millitech to HAMSR specifications.

Fig. 6a. 118-GHz receiver

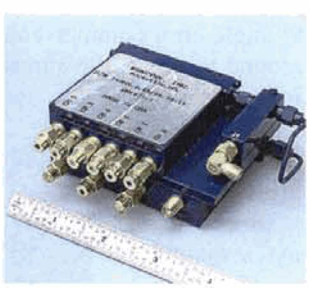

Fig. 6b. 118-GHz filter bank

E. Spectrometers

Miniaturized filter banks sample the oxygen and water vapor line shapes. The required center frequencies, bandwidths and resulting brightness temperature sensitivities for a 25 ms integration time are given in Table I. The out of band rejection is specified at >40 dB at twice the filter bandwidth or greater for filters with center frequencies less than 4 GHz and >30 dB for filters greater than 4 GHz, to simplify the filter design. The filter bank approach was chosen to avoid multiple down conversions, to make the HAMSR system smaller, lighter and less expensive than previous systems. Fig. 6b shows the 118-GHz filter bank, built for IMAS by Reactel, which also built the 183-GHz filter bank for HAMSR. The 53-GHz filter bank was built by ETI for IMAS.

F. Detector-Digitizerss

The 25 IF outputs of the filter bank spectrometers are applied to the detector/digitizers, which detect, amplify, integrate and digitize each channel. HAMSR utilizes eight units, each of which handles four input channels, to process the 25 required channels and provide seven spares. The detectors are off-the-shelf Agilent devices and have high linearity for signal levels less than -15 dBm. The detected outputs are applied to highly stable, wideband op amps for amplification and integration. Digitization is provided by 12-bit analog to digital converters and applied to a storage buffer. The computer system then sequentially polls the buffers of each channel.

G. Digital Subsystem

The digital subsystem manages the acquisition of the 32 channels of data from the detector/digitizers, collects housekeeping and aircraft navigation data; controls and sequences the scan system; and provides mass storage for the data collected. The core of this subsystem is a PC-compatible CPU card with a PC-104 bus and IDE mass storage. The mass storage is a removable ATA Flash PCMCIA card. The most intensive processing in the digital subsystem is the high-speed acquisition of detector/digitizer radiometric data. HAMSR also incorporates measurement of physical temperatures, both for 'first-order' calibration (calibration targets, for example) and for 'second order' housekeeping such as instrument component temperatures. These measurements are handled by two 16-channel 12-bit PC-104 analog to digital converters with appropriate scaling for each parameter. Navigation data from the host aircraft are accessed via a serial port and also stored on the flash card.

H. Packaging

The instrument consists of an open-frame sensor module and an electronics and power module, connected with cables. These can be packaged together in a single enclosure – such as one designed for ground operations, or they can be packaged separately – such as is done for the ER-2 wing pod deployment. The system is therefore quite flexible and can be easily reconfigured for each application. The dimensions of the HAMSR frame are 91 cm x 61 cm, and it weighs 45 kg.

IV. Field Operations

HAMSR can be deployed on an aircraft as well as on fixed and mobile ground platforms. It only requires a free field of view and access to 110-volt power and can operate at a wide range of ambient temperatures and pressures.

A. ER-2 Deployment

For the CAMEX-4 mission HAMSR has been integrated into the forward section of one of the ER-2 wing pods (the so-called superpods), where it has a nadir view through a port hole. Since this section of the pod is normally kept pressurized, a pressure vessel was built that isolates HAMSR from the pod pressure and allows it to operate at ambient flight altitude pressure. This vessel has a circular opening that mates with a circular opening in the bottom of the pod, forming an air tight seal. The HAMSR sensor module is mounted inside the pressure vessel above this window. It is therefore able to get an unimpeded view of the atmosphere, and air can freely enter and exit the instrument compartment. Fig. 7 shows the pressure vessel and HAMSR mounted in the ER-2 wing pod.

Fig. 7a. Pressure vessel

Fig. 7b. HAMSR in ER-2 superpod

Only a thin mylar sheet protects the scan mirrors from possible splatter during takeoff and landing. The electronics module is mounted in the pod, outside the pressure vessel.

HAMSR will also be fitted inside an ER-2 fuselage pod – a small unpressurized tank suspended below the center of the ER-2 fuselage. Here the sensor and electronics modules will be mounted in close proximity. Since the fuselage tank is quite small and few instruments can be accommodated there, it is expected to provide HAMSR with many flight opportunities.

B. Other Aircraft

HAMSR was originally intended to fly on the solar powered series of UAVs under development for the NASA Environmental Research and Sensor Technology program – first on the Centurion and later on the Helios. As that project experienced delays, however, HAMSR was re-targeted to the ER-2. Small enough to fit even inside the UAV wing itself, HAMSR is well suited for these aircraft, and it is likely that it will eventually fly on a solar powered UAV.

Another candidate platform that has been examined is the Proteus, a small piloted experimental aircraft developed by Scaled Composites and designed to stay aloft for extended periods of time. One accommodation concept that has been studied has HAMSR in a small integral pod attached to the side of the fuselage, as illustrated in Fig. 8a. This allows an unimpeded nadir-to-zenith view to one side without interfering with other instruments that would normally be located in the fuselage for nadir or zenith observations. The side position makes it possible to observe upwelling and downwelling radiation separately – useful for radiometric validation.

C. Ground Deployment

One of the planned applications requires atmospheric soundings at a fixed ground location. Although not optimized for upward-looking soundings, HAMSR has nevertheless a number of channels that can be used for that purpose and will yield adequate accuracy. HAMSR is then mounted inside a protective housing with an open aperture that gives a clear view of the atmosphere from horizon to horizon in the scan plane. This is illustrated in Fig. 8b. The enclosure is mounted on a horizontal turntable. This arrangement makes it possible to point HAMSR in any given direction. By motorizing the turntable it is possible to scan out the entire air volume surrounding the ground site, as illustrated in Fig. 10.

Fig. 8a. Deployment on Proteus (concept)

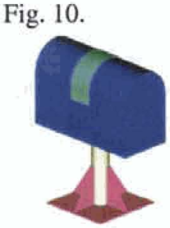

Fig. 8b. Ground enclosure

D. Sampling Approach

The HAMSR scan and data acquisition system is software controlled and entirely programmable. For each application, a desirable goal is to achieve critical spatial sampling (in a Nyquist sense). Since the IFOV is about 6°, the sampling intervals are then chosen to produce 3° scan intervals. For the current CAMEX ER-2 configuration, the system is programmed for a constant scan speed and a 1.1 second scan cycle. This requires integration intervals of about 9.3 ms. Fig. 9 illustrates the scan pattern projected on the ground. The

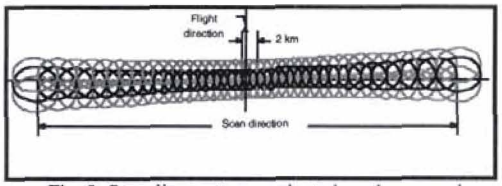

Fig. 9. Sampling pattern projected on the ground

ER-2 has a ground speed of 0.21 km/s – equivalent to about 3/4° per second – and therefore four consecutive scans can be averaged in the flight direction to form 3°x 3° sampling cells. These can be further averaged to form contiguous 6°x 6° cells – representing a more common sampling scheme, where the sampling cells are equal to the IFOV and do not overlap.

For ground deployment, the atmospheric scene changes much more slowly, and the sampling intervals (or the averaging) can be extended considerably. The result is to increase the effective sensitivity and accuracy. Fig. 10 illustrates a conceptual sampling pattern from the ground.


Fig. 10. HAMSR ground scan pattern

E. Applications

Two missions have so far been identified, and several others are under consideration.

HAMSR was selected to participate in CAMEX-4. The main objective of this field campaign – operating from the Jacksonville, FL Naval Air Station from August 15 to September 26 2001 – is to investigate hurricanes, with special emphasis on the "landfall problem". Here HAMSR, positioned in an ER-2 wing pod, as described above, will provide key measurements of the temperature, water vapor and liquid water distribution in and around hurricanes. Important information about scattering from liquid and ice particles will also be obtained from the HAMSR observations.

The second application – originally planned to take place this year but now delayed until 2002 because of CAMEX – consists of using HAMSR to determine total water vapor burden along Deep Space Network antenna lines of sight. This will be used to estimate path delay, an important parameter for investigations such as the Cassini radio occultation experiment. The purpose of this task is to determine if a 183-GHz water vapor radiometer, as used in HAMSR, can be used to measure path delay with sufficient accuracy. The potential savings in size and cost over the large low-frequency water vapor radiometers traditionally used for this purpose are considerable.

Other potential applications, some being actively pursued, fall into three categories:

a) Aircraft field campaigns – where HAMSR provides core measurements of the atmosphere from the ER-2 or other suitable aircraft platform.

b) Validation campaigns – where HAMSR is used for radiometric or geophysical validation of satellite systems, either from aircraft under-flights or from fixed ground deployments. Candidate missions include Aqua, NPP, and NPOESS.

c) Technology validation – where HAMSR is used as a testbed for new components or design concepts being developed for future missions. Possibilities include flight testing of 183-GHz MMIC receivers and new spectrometers. Due to the great similarity to ATMS, HAMSR is an ideal testbed for new ATMS technology. The open, reconfigurable design utilized for HAMSR makes that particularly feasible.

V. Conclusion

The IMAS program sponsored a multi-million-dollar development of MMIC technology suitable for microwave atmospheric sounding. As a result of this effort, which involved two contractors (TRW and Lockheed Martin/Sanders – now BAE Systems), the state of the art was pushed forward significantly. In particular, TRW delivered functional 53 and 118 GHz receivers, which have now been incorporated into the HAMSR sounding system. Compact spectrometers (filter banks) meeting the IMAS spectral specifications were also developed and delivered, and those have also been used in HAMSR. Although the IMAS program was terminated before 183-GHz MMIC receivers could be developed, both contractors demonstrated LNAs at 170-200 GHz, and that development is now being carried to maturity by others.

HAMSR has implemented many of the IMAS design elements and utilizes the technology prototypes developed for IMAS, supplemented with HAMSR-specific components. It represents a great stride forward in sounder design and technology. Early test results also indicate that the instrument will perform in the field as well as in the laboratory. All indicators point to the likelihood that HAMSR is on its way to become a very valuable scientific instrument that will make significant contributions to the NASA Earth Science mission.

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