Hurricane Research with the High Altitude MMIC Sounding Radiometer

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Abstract- **The High Altitude MMIC Sounding Radiometer (HAMSR) is a new remote sensing instrument designed and built under Instrument Incubator Program sponsorship. Essentially completed in 2000 for ground based operation, and further enhanced in 2001 for aircraft based operation, it was selected for participation in the Fourth Convection and Moisture Experiment (CAMEX-4). The primary objectives of this NASA sponsored field campaign, operating out of the Jacksonville, FL Naval Air Station during August and September of 2001, were to study hurricanes and tropical convective processes. HAMSR is well suited for such missions, since it provides measurements that can be used to infer the 3-D distributions of temperature and water vapor in the atmosphere, even in the presence of clouds. Information related to scattering from ice particles aloft as well as precipitation can also be inferred. During CAMEX-4 HAMSR was mounted in a wing pod of a NASA ER-2 research aircraft, which operates at an altitude of 65,000 feet – high enough to overfly a hurricane. Although the early part of the 2001 hurricane season was relatively quiet, a number of interesting observations were made and a large amount of data was collected for further analysis. We present preliminary results for hurricane Erin, made on 9/10/01, which illustrate the very substantial scattering that can be observed over intense convective and precipitating systems, as well as other characteristics of a hurricane. The HAMSR observations are expected to make a significant contribution to the advancement of our knowledge of hurricanes and the processes that drive them.**

I. 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 first atmospheric sounder to use receivers based on monolithic microwave integrated circuits (MMICs). It 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 and a common field of view. 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 emerging from 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 was subsequently upgraded for deployment on NASA's high altitude ER-2 aircraft. The first test flights were successfully carried out in July 2001, and HAMSR then participated in the fourth Convection and Moisture Experiment (CAMEX-4).

The 2001 hurricane season was unusually quiet during CAMEX-4. Several hurricanes were nevertheless investigated, along with a number of other intense convective systems. The large data set resulting from this campaign is now being analyzed, and the HAMSR data are expected to contribute significantly to the body of knowledge and understanding of tropical cyclones.

Although HAMSR is emerging as a valuable scientific research tool, it was intended to demonstrate new concepts developed for the next generation of satellite sounders. HAMSR is built around a core of miniaturization technology developed under the short-lived Integrated Multispectral Atmospheric Sounder (IMAS) program - and thus carries NASA's considerable investment in this area to fruition. HAMSR uses a flexible design that makes it easily reconfigurable. This makes it ideally suited as a testbed for new components. Technology and design concepts first demonstrated with HAMSR will be used on the future National Polar-orbiting Operational Satellite System (NPOESS) and operated in space for the first time on the NPOESS Preparatory Project (NPP) mission. HAMSR will continue to be used in the future as a testbed to validate new technology as well as to support scientific missions.

II. THE INSTRUMENT AND ITS MEASUREMENTS

HAMSR is a passive microwave radiometer, which measures the thermal radiation emitted from the atmosphere and the surface below. It has three receivers, which detect part of this emission in three spectral bands. Each receiver is attached to a spectrometer – a filter bank, which essentially tunes the receiver to a number of narrow spectral channels simultaneously. This allows portions of the spectrum of the radiation to be determined.

HAMSR has 25 spectral channels in those three bands, between 50 and 190 GHz. Fig. 1 shows the atmospheric spectrum in this region. Band I has 10 channels near the 118-GHz Oxygen line and Band II has 8 channels in the 50-70 GHz Oxygen complex. Both are used for temperature sounding. Band III has 7 channels near the 183-GHz water vapor line and is used for water vapor sounding. The characteristics of these channels are listed in Table 1.

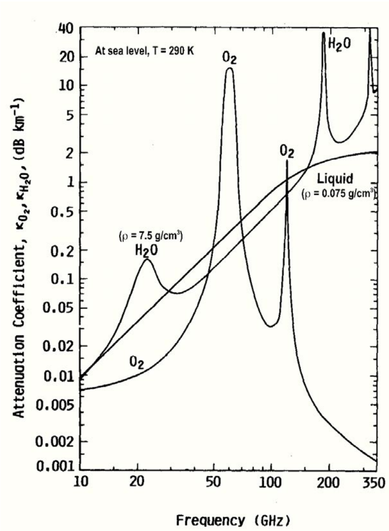


Fig. 1. Microwave absorption spectrum

Fig. 2 shows the resulting weighting functions in a standard atmosphere. Bands I and II have nearly identical weighting functions and are therefore essentially redundant. Thus, although Band I was not operational during CAMEX-4, full temperature and humidity sounding capability was nevertheless achieved.

For CAMEX-4 HAMSR was installed in the forward compartment of the right wing pod of the NASA ER-2. Thermal radiation from the atmosphere enters through a window in the bottom of the pod into two closely spaced apertures. Each illuminates a scan mirror, which reflects the incoming radiation into the receivers. The mirrors are mounted at a 45° angle on a common scan axis, and by rotating them around this axis the atmosphere below is scanned in a direction perpendicular to the scan axis – which lies in the flight direction. The instantaneous field of view (IFOV) is a cone with an angle of 5.7°. The scan mirrors are programmed to rotate at a constant speed,

TABLE I
HAMSR MEASUREMENT SPECIFICATIONS

Ch #	Center freq. [GHz]	Offset [GHz]	Bandwidth [MHz]	Wt-func. peak [mb or mm]
I-1	118.75	-5.500	1500	Sfc/[30 mm]
I-2	“	-3.500	1000	Surface
I-3	“	-2.550	500	Surface
I-4	“	-2.050	500	1000 mb
I-5	“	-1.600	400	750 mb
I-6	“	-1.200	400	400 mb
I-7	“	±0.800	2x400	250 mb
I-8	“	±0.450	2x300	150 mb
I-9	“	±0.235	2x130	80 mb
I-10	“	±0.120	2x100	40 mb
II-1	50.30	0	180	Sfc/[100 mm]
II-2	51.76	0	400	Surface
II-3	52.80	0	400	1000 mb
II-4	53.596	±0.115	2x170	750 mb
II-5	54.40	0	400	400 mb
II-6	54.94	0	400	250 mb
II-7	55.50	0	330	150 mb
II-8	56.02 & 56.67	0	270 & 330	90 mb
III-1	166.31	0	4000	[11 mm]
III-2	183.31	±10.0	2x3000	[6.8 mm]
III-3	"	±7.0	2x2000	[4.2 mm]
III-4	"	±4.5	2x2000	[2.4 mm]
III-5	"	±3.0	2x1000	[1.2 mm]
III-6	"	±1.8	2x1000	[0.6 mm]
III-7	"	±1.0	2x500	[0.3 mm]

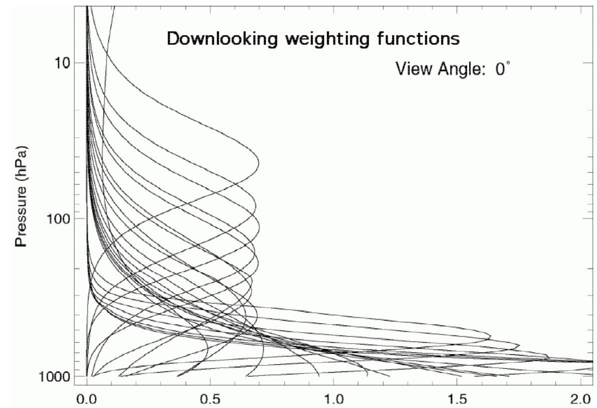


Fig. 2. HAMSR down-looking weighting functions for nadir

with one full rotation every 1.1 seconds, and the data acquisition system is programmed to integrate the received signals in 9 ms time slices. During such a sampling period the “beams” move about 3°, i.e. about half of the IFOV. On the ground at nadir the IFOV projects to a circle with a diameter of about 2 km when the instrument is at the normal ER-2 flight altitude of 20 km, and the spacing between adjacent samples is about 1 km. As the mirrors scan away from nadir, the “footprints” projected on the ground become elliptical and grow in size. The result is a “scan line” swath, which for CAMEX-4 was about 40 km wide on the ground. This is illustrated in Fig. 3. With an air speed of 0.21 km/s - the cruising speed of the ER-2, the spacing between adjacent scan lines in the direction of flight is about 1/4 km.

During post processing of the data, two sets of composite sampling cells are formed – with a size of 1 km and 2 km at nadir, respectively – by averaging adjacent individual samples. The radiometric sensitivity of HAMSR ranges from 0.2 to 0.4 K for a composite cell, depending on channel, and absolute calibration accuracy is better than 0.5 K. Retrieval accuracy depends on atmospheric conditions and is around 2 K for temperature profiles, with a vertical resolution of about 2-3 km. For water vapor profiles it is around 15-20%, with a vertical resolution of 3-4 km. Liquid water profiles can be derived with an accuracy of 40% and a vertical resolution of 4 km. We expect to make significant improvements in the measurement accuracy – absolute radiometric accuracy as well as retrieval accuracy – over time.

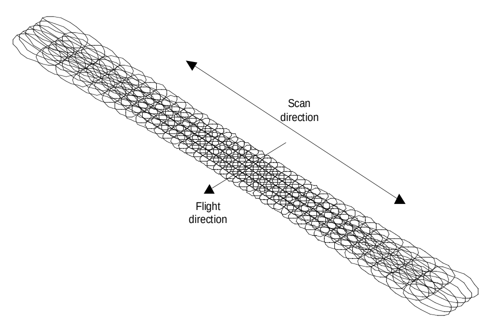


Fig. 3. Scan pattern – ground swath

HAMSR is the first aircraft sounder with both temperature and humidity sounding capabilities, a very important advantage in situations with high atmospheric variability, such as in and around hurricanes and other weather systems. The current generation of satellite microwave sounders – the Advanced Microwave Sounding Unit, operated by the National Oceanic and Atmospheric Administration on its polar orbiting weather satellites and now also by NASA on its Aqua research satellite, consist of separate temperature and humidity sounding units, which are not perfectly aligned with each other. Only the next generation of satellite instruments will implement a co-boresighted approach such as HAMSR has.

III. The CAMEX-4 Mission

The Fourth Convection and Moisture Experiment was conducted in collaboration with the NOAA Hurricane Research Division and the US Weather Research Program between August 16 and September 24, 2001. Its objective was to study hurricanes and tropical convective processes, with particular emphasis on cyclone development, intensification, and landfall. NASA deployed its ER-2 and DC-8 aircraft, both based at the Jacksonville, FL Naval Air Station - NOAA deployed its P-3 aircraft - and operated them in the vicinity of hurricanes and other convective systems under study. Generally, the P-3 flies at a low altitude of a few thousand feet, often through the eye of a hurricane, while the DC-8 is usually flown at mid-altitude around the perimeter. The ER-2 operates at 65,000 feet and can therefore fly over a hurricane and study it from above. The ER-2 platform is equivalent to a satellite platform, but with the great advantage of providing a much closer view and being able to stay over the target for several hours at a time.

All aircraft were equipped with a number of active and passive remote sensing instruments as well as in-situ air probes, and all were able to release so-called drop sondes, which transmit atmospheric measurements by radio as they descend to the surface. Several ground stations provided radar and other observations, and additional “ground truth” was collected from standard sources, such as weather stations and ocean buoys.

The role of HAMSR, which was deployed on the ER-2 during the entire duration of CAMEX-4, was to provide observations of a number of key atmospheric variables in and around the systems being studied. From the HAMSR measurements will be derived the vertical distribution of temperature, water vapor and cloud liquid water, which will provide a 3-D view of those variables in the vicinity of the flight tracks. The HAMSR measurements will also be used to study scattering from suspended ice particles, often associated with intense convective precipitation.

Although the 2001 hurricane season was relatively quiet during CAMEX-4, several hurricanes appeared and were studied, although none made landfall. (One exception was hurricane Gabrielle, which passed over Florida; however, the landfall could not be fully monitored because the base of operations, also in Florida, had to be closed down due to the severe weather conditions.) In addition, smaller convective systems and precipitation events were also studied. The CAMEX-4 field campaign yielded a wealth of data, and the analysis effort is already well under way.

IV. HAMSR Data

Although CAMEX-4 represented the very first field deployment for HAMSR, the instrument performed remarkably well. A total of 60 hours worth of flight data was collected, which is equivalent to an up-time of approximately 80%. A few minor early problems were quickly rectified, and only during the final week did the performance degrade in a serious way. (This was due to a power supply failure, which caused crucial components to degrade or fail.) A data catalog, describing the details of each flight mission (destination, objectives, etc.) along with HAMSR instrument performance and the data collected, has been assembled and forms the basis for the analysis effort that is now under way.

The data are taken through a number of processing steps. The first step is to produce calibrated brightness temperatures, where the observations of two internal calibration targets, viewed every scan cycle, and measured temperatures of those targets, are used to estimate the radiometric transfer function. This function is used to convert the raw digital counts produced by the instrument to physical brightness temperatures. Known instrument biases are also removed during this step.

The second step is to bin the data into larger composite sampling cells. While the instantaneous field of view is about 2 km at nadir, the sampling spacing is about 1 km in the scan direction and about 1/4 km in the flight direction. Four of these are combined to form 1-km cells and 16 are used to form 2-km cells. This process trades reduced spatial resolution for improved noise levels.

The final step is to perform geophysical retrievals from the brightness temperatures, using procedures similar to those used for satellite instruments. For this step it is also necessary to obtain estimates of surface conditions: temperature, pressure and sea state. Resulting profiles of temperature and water vapor and liquid water densities are derived for the entire air volume scanned out by the instrument, from nadir to the swath edges. However, the standard retrieval method fails in precipitating areas. Therefore, it is also important to apply a rain flag filter. A rain indicator can be obtained from other sources.

V. Some CAMEX Results

Although the analysis of the HAMSR data has just started, some preliminary results will be discussed here. After a survey of the data catalog, certain flights have been identified as particularly interesting. One of those is the flight over hurricane Erin on September 10, 2001. Although this tropical cyclone was only briefly classified as a hurricane, it exhibited classical hurricane features, with a well defined eye. Fig. 4 shows the flight track over Erin, with a background image of the storm obtained from the geostationary satellite GOES-8. A so-called “figure-four” pattern was flown, which yielded three passes over the eye of the storm.

In Fig. 5 the observations in three of the 8 temperature sounding channels are shown. Fig. 5a shows a lower stratospheric channel, sensing the atmosphere just below the aircraft, 5b shows a mid-lower tropospheric channel, and 5c shows a channel that normally senses the atmosphere near the surface. A subset of humidity sounding channels is shown in Fig. 6. These normally sense the atmosphere in the mid to lower troposphere, since that is where the humidity and clouds are distributed. We will discuss two features in the Erin data.

The first feature is apparent upon a cursory examination of the lowest-level humidity channel in particular. Very large and very sharp variations in the brightness temperature can be seen in the vicinity of the center of the storm. This is pre-

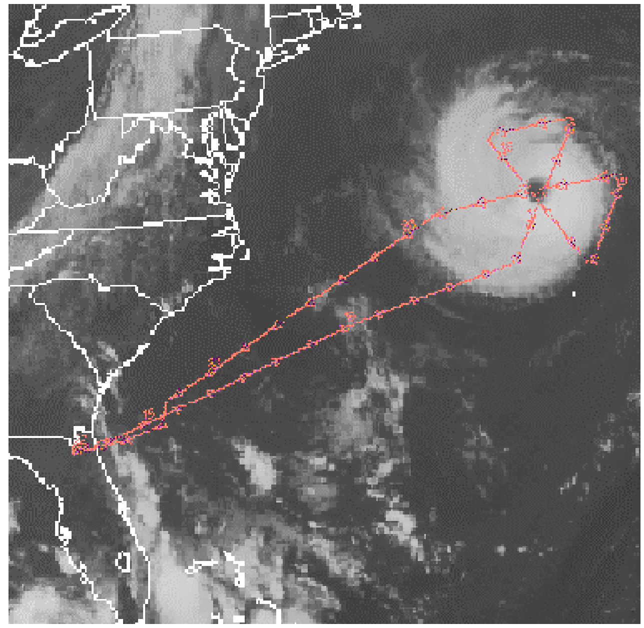
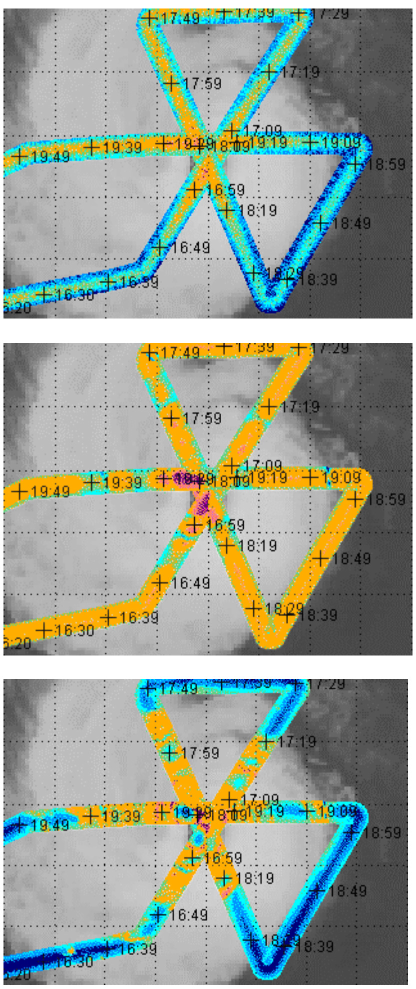


Fig. 4. ER-2 flight over hurricane Erin, 9/10/01



(a)

56.02 GHz

(90 mb;17 km)

(b)

53.6 GHz

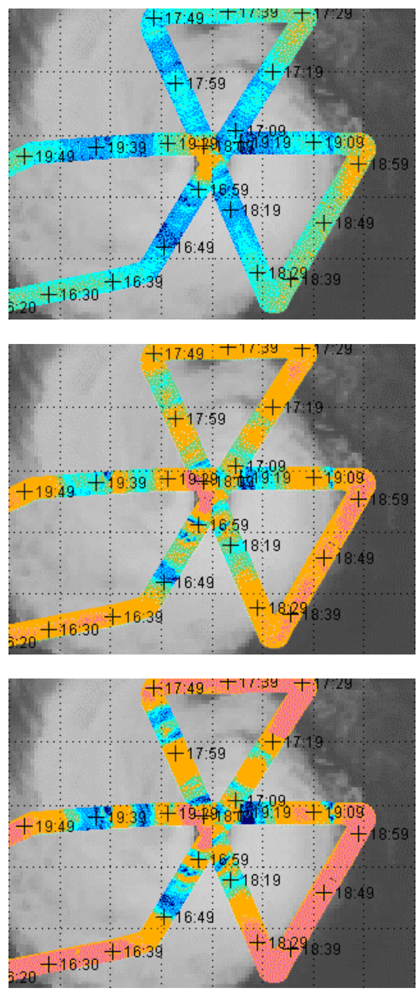
(750 mb, 2.5 km)

(c)

50.3 GHz

(Surface)

Fig. 5. Temperature sounding channels



(a)

183±1 GHz

(500 mb;6 km)

(b)

183±3 GHz

(600 mb, 4 km)

(c)

166 GHz

(800 mb, 2 km)

Fig. 6. Humidity sounding channels

sumed to be caused by scattering from ice particles aloft above very intense convective cells in the vicinity of the eye walls. The resulting brightness temperature depression can reach beyond 100 K, as can be seen in Fig. 7, which shows the brightness temperatures of the humidity channels at nadir along the entire flight track. The eye of the storm is passed three times – near 17:05, 18:10, and 19:25. The scattering signature, which consists of a severe depression of brightness temperature in the most transparent channel and nearly none in the most opaque channel, is apparent in several narrow bands outside the eye – i.e. in the eye walls. It may also be noted that another scattering signature is a reversal of the normal brightness sequence, from warm-to-cold to cold-to-warm, when cycling through the channels as listed in Table I, i.e. in order of transparency. This is because the radiation seen by the transparent channel originates almost exclusively from below the scattering level. Conversely, the radiation seen by the opaque channel originates almost exclusively from above the scattering level.

The second feature, a substantial temperature anomaly inside the eye, can be seen in Fig. 8, which shows the brightness temperatures of the temperature sounding channels at nadir along the flight track. This plot shows a slightly elevated temperature even in the stratospheric Ch. 1. At the upper-tropospheric Ch. 4 the anomaly is more than 5 K. Although firm conclusions cannot be drawn until full retrievals have been made, it is clear from these figures that the eye of the hurricane is substantially warmer and drier than the surrounding atmosphere.

As the data analysis proceeds, these features will be quantified, and comparisons will be made with observations obtained with other instruments aboard the ER-2 and drop sondes. Particular emphasis will be made on an examination of the scattering signature, and an attempt will be made to correlate it with precipitation rates determined by other means. This is currently of particular interest to those who are engaged in the planning and design for the upcoming Global Precipitation Mission, as well as those who are attempting to develop rain retrieval algorithms using high-frequency microwave humidity soundings from space. It is expected that the HAMSR data, which will be made available to a number of investigators, will contribute significantly to this effort.

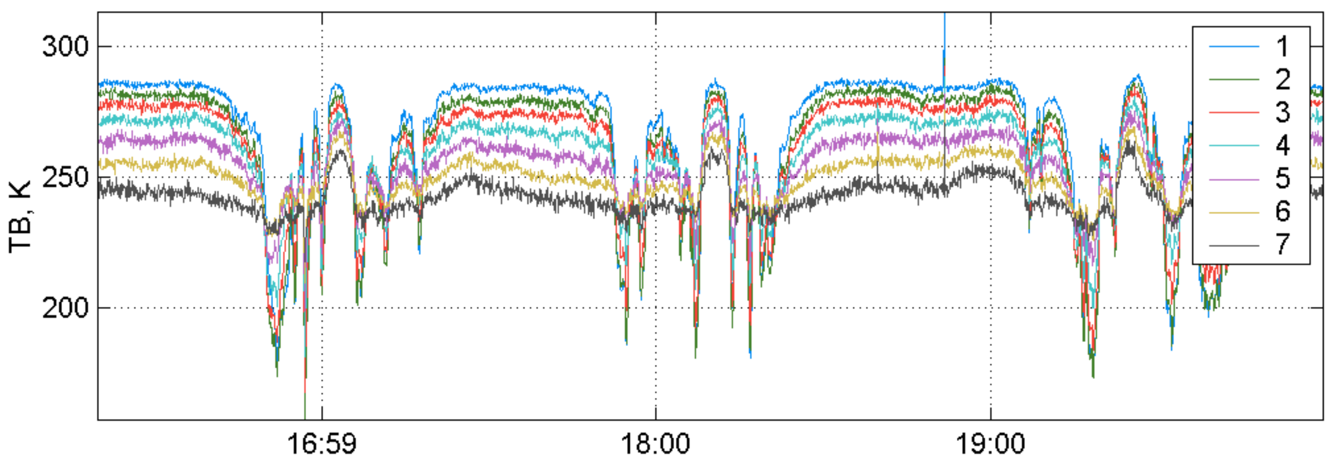


Fig. 7. Humidity channel brightness temperatures at nadir from Erin flight

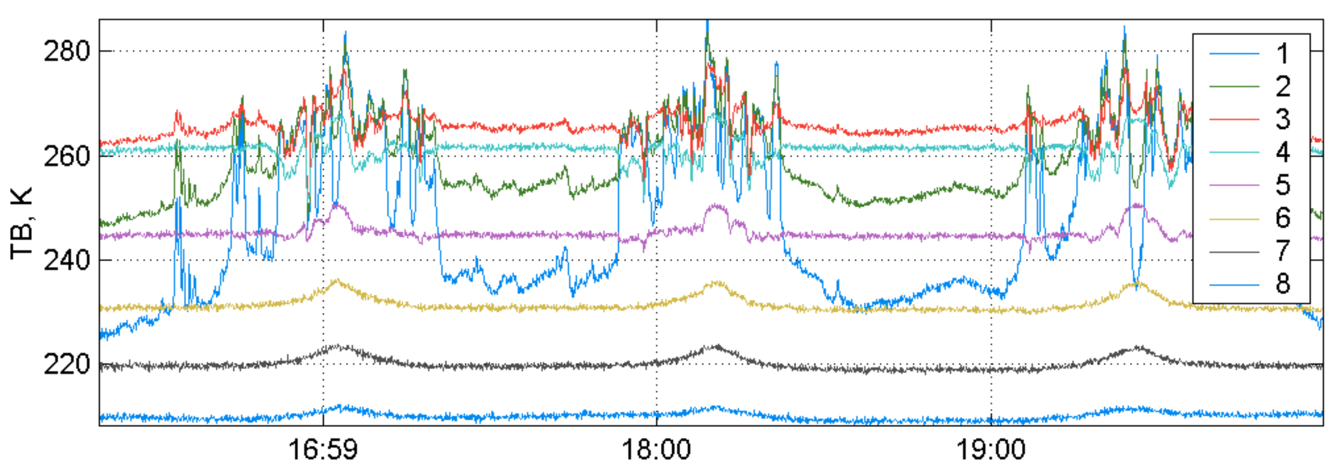


Fig. 8. Temperature channel brightness temperatures at nadir from Erin flight

VI. Conclusion

Besides demonstrating exciting new technology and new design concepts, HAMSR is on the way to becoming a very useful and mature scientific tool. It has already generated a rich data set of hurricane observations, which is expected to add to the body of knowledge about tropical cyclones and related phenomena. We look forward to analyzing this data and to participating in new field experiments in the future.

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