Lecture 9 (10-17-83)

17 October 1983

ATMOSPHERIC SOUNDINGS OF TEMPERATURE AND MOISTURE FROM SATELLITES

I. Nature of measurements.

A. MOST soundings obtained by earth-pointing sensors measuring thermal emission of a gas.

Figure 9-0(a) (Vu-graph)

1. Temperature: Infrared measurement of CO_2 (HIRS, VAS, SSU)
   a. 15 μm band (13.3 to 15.0)
   b. 4.3 μm band (4.24 to 4.57) Actually a mix of CO_2 and N_2O.
2. H_2O by Infrared measurement (most absorption) (least) (HIRS, VAS)
   a. Different wavelengths from 6.70 μm to 13.0 μm
3. Temperature by microwave measurement of O_2 (MSU, AMSU)
   a. 50 to 58 GHz
4. Water vapor by microwave measurement of H_2O (AMSU)
   a. 166 to 183 GHz.

B. For temperature, assume gas is uniformly mixed in atmosphere, and assume its amount. For water vapor, use the above determination of temperature and solve for the amount of water vapor. [That is, the emission of energy by the gas is a function of its composition, amount and temperature.]

1. Complicating factors:
   a. Surface emission - must make corrections.
      - Problem over land in microwaves. - Limited to oceans so far. Maximum horizontal resolution desired (AMSU = 40 km at nadir)
   b. Clouds interference in infrared - apply correction schemes; limit accuracy. Minimize by high resolution and contiguous fields of view between adjacent observations; apply Smith's scheme for cloud correction.

Temperature

	Gas	Detector
4.3 μm band (4.24 - 4.57)	CO_2, N_2O	InSb
15 μm band (13.3 - 15.0)	CO_2	HgCdTe
50 - 58 GHz band	O_2	Dike

Water Vapor

I.R. in range 6.70 - 13.0 μm	HgCdTe
Mwave range 166 - 183 GHz	Dike

InSb = Indium Antimonide
HgCdTe = Mercury Cadmium Telluride (cooled)
Dike = Dike type microwave radiometer

Figure 9-0 (a)

FORM OF RADIATIVE TRANSFER EQUATION

$$I(\nu) = B_s \tau_s(\nu) + \int_{\tau_s}^{1} B \, d\tau(\nu)$$

$$= \underbrace{I_s(\nu)}_{\text{surface term}} - \underbrace{\int_0^{p_s} B(\nu, T) \overbrace{\frac{d\tau}{dp}}^{\text{weighting function}} dp}_{\text{Integrated effect of atmospheric composition, mass and temperature}}$$

B = Planck radiance
τ = transmittance
ν = frequency
s = surface

Figure 9-0 (b)

C. Rain interference in microwaves – try to detect by comparison of different channels and eliminate.

C. Limitations on vertical resolution (due to pressure-broadening of the lines in the radiation emission spectrum in the lower part of the atmosphere, and the instrument having to "see through" the intervening atmosphere.

1. Use of limb scanning – In IR, limited to stratosphere, above clouds.
2. Limb scanning with microwaves? – Need high resolution / narrow beam width = big antenna.
3. Resolve a single radiation line or fraction of a line: SSU – Q branch of 15 μm CO_2
   AMSU – Two adjacent O_2 lines at { 57,290,021.8 MHz / 57,290,666.2 "
   H_2O line at 183.31 GHz

   Operational sensors following this approach.

D. General configuration of sensors.

1. Detectors:

(See Figure 4-0(a))

(a) 4.3 μm IR – Indium Antimonide (InSb)
(b) 15 μm IR – Mercury cadmium Teluride (HgCdTe), cooled
(c) Microwave – Dike Radiometer.

2. Spectral resolution:

(a) IR – interference filters (HIRS, VAS)
(b) IR – gas cell (SSU, CO_2)
(c) IR – grating (SIRS)
(d) IR – Interferometer (IRIS)
(e) μwaves – electronic filters (MSU, AMSU)

3. Spatial resolution:
   (a) IR - reflective optical telescope
   (b) μwaves - reflective antenna (side lobe problems)
4. Most important characteristics are:
   (a) Sensitivity
   (b) Precision
   (c) Means of calibration to achieve accuracy.
   (d) Avoiding or correcting for contamination (surface radiation, clouds, precipitation)

E. Derivation of temperature or moisture from a set of radiances.

Figure 9-0(b) (Vu-graph) Based on solving some form of the radiation transfer equation, e.g.:

$$I(\nu) = B_s \tau_s(\nu) + \int_{\tau_s}^{1} B \, d\tau(\nu) = I_s(\nu) - \int_0^{p_s} B(\nu,T) \frac{d\tau}{dp} dp$$

(Assumes no cloud contamination)

$I(\nu)$: measured intensity

$B_s \tau_s(\nu)$: surface term

$\int_{\tau_s}^{1} B \, d\tau(\nu)$: contains integrated effect of composition, amount and temperature in atmosphere

$\frac{d\tau}{dp}$: weighting function

ν = frequency of radiation

B = Planck radiance (B_s = Planck rad. at the surface)

τ = transmittance (τ_s = transmittance at the surface)

1. One such equation for each observation in each spectral interval. Problem is to invert the set of simultaneous integral equations to solve for desired temperature profile or profile of gas amount (e.g., H_2O or O_3).
   - Solution is not unique and, with noise, can be unstable.
   - Many approaches have been proposed and tested.
   - Also has been difficult to prescribe the various transmittances with the required accuracy.

2. As a result, current operational method based on W. Smith's technique using a
   linear regression method
   to convert measured radiances to atmospheric temperatures (or water vapor).
   - Regression coefficients revised weekly using a statistical data base of nearly colocated satellite measurements and radiosondes, accumulated in 5 latitude belts in the preceding several weeks. (Biased to N. Hem. continental areas!)
3. Infrared observations must be corrected for the presence of clouds (and eliminated in overcast areas).
   - "Clear radiances" are calculated in partly cloudy areas using the procedure of W. Smith, ~~cloudy~~, as modified by McMillin and Dean. (Modification became operational in June 1980.)

References:
- Smith, W.L. (1968): An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements. Mon. Wea. Review, V. 96 pp 387-396.
- Smith, W.L., and H.M. Woolf (1976): The use of eigenvectors of statistical covariance matricies for interpreting satellite sounding radiometer observations. J. Atmos. Sci., V. 33, pp. 1127-1150.
- Smith, W.L., H.M. Woolf, C.M. Hayden, D.Q. Wark and L.M. McMillin (1979): The TIROS-N operational vertical sounder. Bull. Amer. Meteor. Soc., V. 60, pp. 1177-1187.
- McMillin, L.M., and C. Dean (1982): Evaluation of a new operational technique for producing clear radiances. J. Appl. Meteor., V. 12, pp. 1005-1014.
- Phillips, N.A. (1981): Cloudy winter satellite temperature retrievals over the extratropical northern Hemisphere oceans., Mon. Wea. Review, V. 109, 652-659.

Re potential moisture soundings:
- Hayden, C.M., W.L. Smith, and H.M. Woolf (1981): Determination of Moisture from NOAA polar orbiting satellite sounding radiances. J. Appl. Meteor., V. 20, pp 450-466.

4. Operational moisture soundings from TOVS infrared radiance measurements are generally considered unsatisfactory, primarily because of cloud contamination. Hayden, et.al. (1981) present a method which they feel would be useful in describing the moisture - particularly horizontal gradients - in the two layers, surface - 700 mb, and 850 - 500 mb. Scheme is not totally objective and requires subjective editing based on cloud images and horizontal consistency; therefore, NESS cannot implement operationally.

5. Microwaves - limited to the 4-channel MSU (1 "window", 3 temp.)
   - Used as "quality control" on the IR soundings with partial cloud cover.
   - Provides ~~all the~~ many information in the "cloudy" cases. (4 TIRS channels peaking in stratosphere are also used.) The NESS operational system has been modified to incorporate the suggestions of N. Phillips (1981). (It uses maritime radiosondes - islands + ships - only in the colocation data base, and these data classified by sea surface temperature.)
   - Not used when land fills a significant part of field of view.

II. TIROS Operational Vertical Sounder (TOVS) on Polar Orbiter.

A. [I will not dwell on the details of the sounding instruments or retrieval techniques. For completeness I will show the TOVS channel specifications.]

Figure 9-1 (Vu-graph) TOVS Channels.
(Similar info given in lecture 4 for VAS, lecture 5 for GOES-NEXT + AMSU.)

Fig. 9-1

TIROS OPERATIONAL VERTICAL SOUNDER

HIRS/2

CHANNEL	FREQ.	WAVELENGTH	PRIN. GASES	LEVEL PEAK CONTR.
1	668.5 cm^{-1}	14.96 μm	CO_2	30 MB
2	680.0	14.71	"	60
3	690.0	14.49	"	100
4	703.0	14.22	"	400
5	716.0	13.97	"	600
6	733.0	13.64	CO_2/H_2O	800
7	749.0	13.35	"	900
8	900.0	11.11	WINDOW	Surface
9	1030.0	9.71	O_3	25 MB
10	1225.0	8.16	H_2O	900
11	1365.0	7.32	"	700
12	1488.0	6.72	"	500
13	2190.0	4.56	N_2O	1000
14	2210.0	4.52	N_2O	950
15	2240.0	4.46	CO_2/N_2O	700
16	2270.0	4.41	"	400
17	2360.0	4.24	CO_2	5
18	2515.0	3.98	WINDOW	Surface
19	2660.0	3.76	"	"
20	14500.0	0.69	"	"

STRATOSPHERIC SOUNDING UNIT (SSU)

1	668.0	14.97	CO_2	15 MB	* HIGH SPECT. RES. Q BRANCH.
2	668.0 *	14.97	"	4	
3	668.0	14.97	"	1.5	

MICROWAVE SOUNDING UNIT (MSU)

1	50.30 GHz	5.96 mm	WINDOW	Surface
2	53.74	5.58	O_2	700 MB
3	54.96	5.46	"	300
4	57.95	5.18	"	90

Figure 9-1

Nadir resolutions:		Scan angle either side of nadir:
HIRS/2	20 km dia.	49.5°
SSU	147	40.0°
MSU	109	47.4°

B. Comparison of TOVS soundings with radiosondes (not error, because of sampling differences and radiosonde errors.)

✓ Figure 9-2 (slide) Mean difference ~~(TARM-2 Mean much improved)~~
- Clear and partly cloudy (N*)
- New and old cloud correction scheme (see McMillin & Dean, 1981)
- These data for 20 May - 2 June 1980, 30°-60°N. latitude belt. (~3000 soundings)

✓ Figure 9-3 (slide) RMS differences same data base.

TARM-2 Also reduced no. of "Cloudy" (MSU) soundings from 42% to 21% of Total. (June 1980)

- Large deviations in stratosphere, probably due to R/S errors (radiation).
- In both mean & RMS, note pronounced improvement in surface layers.

Figure 9-4 (Vu-graph) - From N. Phillips (1981).

MISSING Cloudy soundings considerably improved in 1981
- Reduction in bias particularly important for NWP.

Figure 9-5 (Vu-graph) -
Current operational TOVS soundings compared to R/S.

(From May WMO-water papers, 1983)

- Problem of comparing with radiosondes (r/s). Operational comparisons (and development of regression coefficients) use satellite radiances & r/s that are within ±3 hrs. and 250(?) km! There are large, natural variations in space and time. R/S is nearly instantaneous in space and time; satellite provides volumetric averge. Also r/s is not error-free.

Fig. 9-2

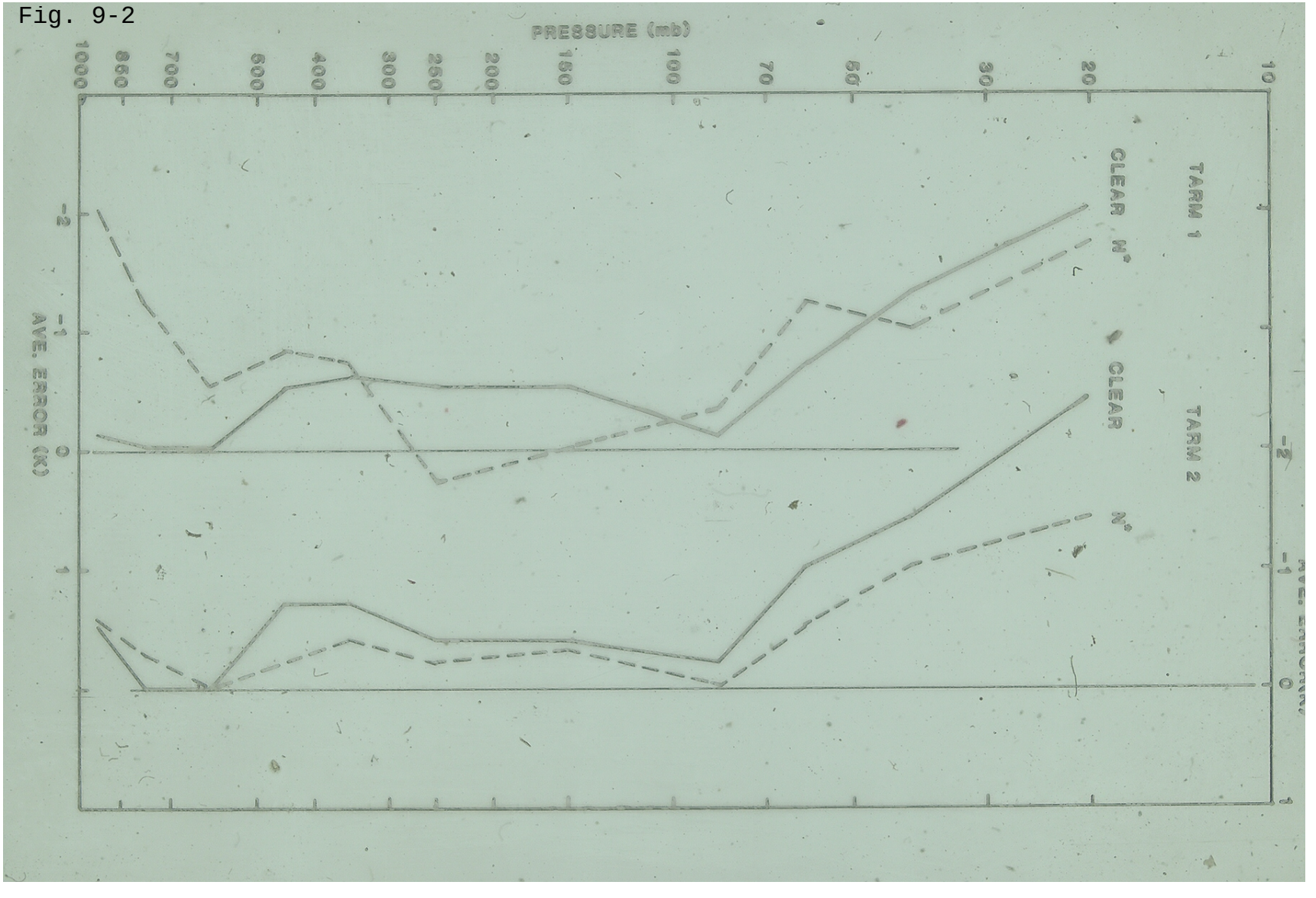
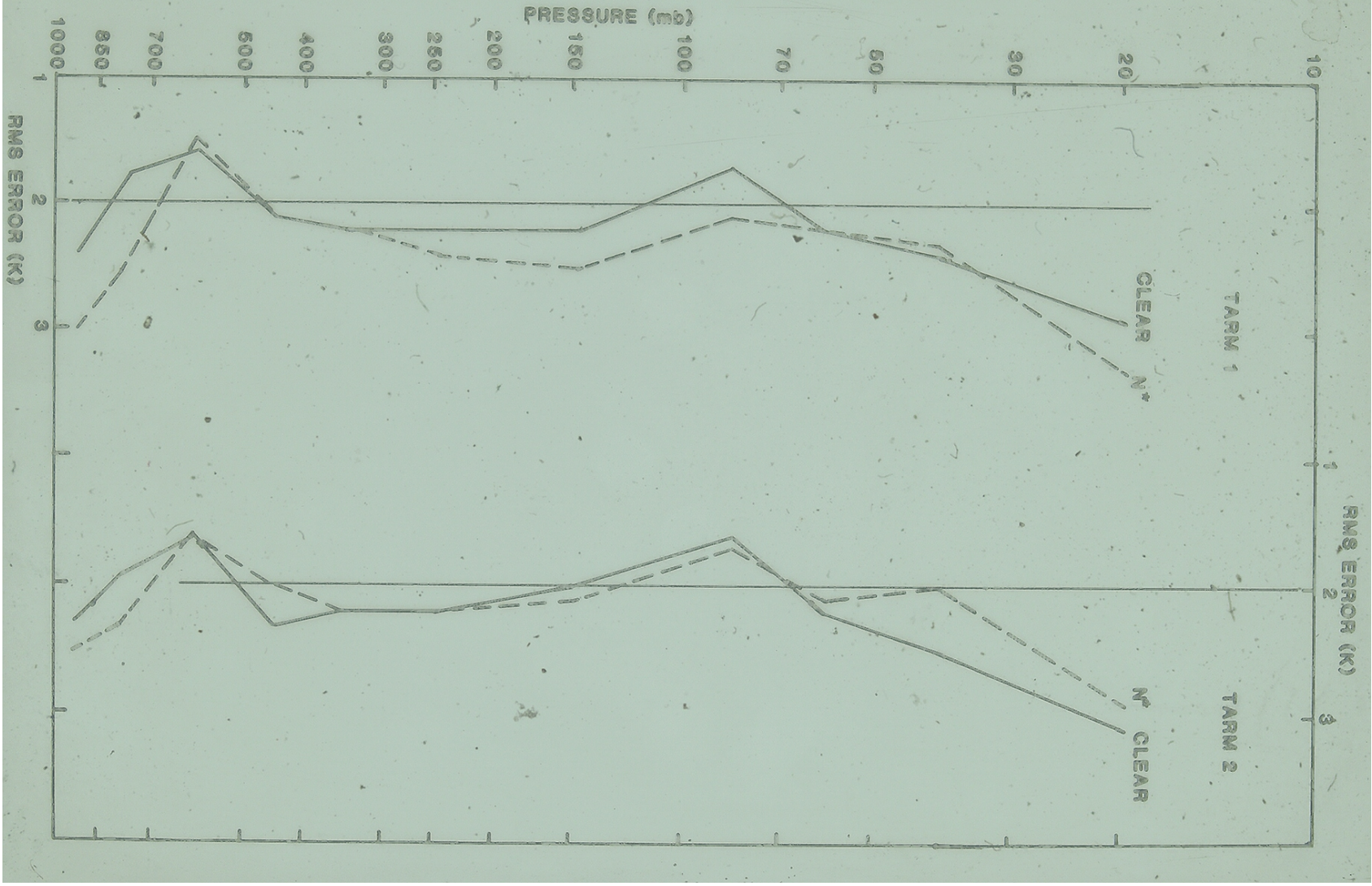

PRESSURE (mb)
1000
850
700
500
400
300
250
200
150
100
70
50
30
20
10
AVE. ERROR (K)
-2
-1
0
1
TARM 1
TARM 2
CLEAR N°
CLEAR N°

Fig. 9-3


PRESSURE (mb)
1000
850
700
500
400
300
250
200
150
100
70
50
30
20
10
RMS ERROR (K)
1
2
3
CLEAR
N*
TARM 1
N* CLEAR
TARM 2

Vu-Graph 9-4 Cloudy Soundings Considerably Improved in 1981

MISSING

Fig. 9-5

PRESSURE	McMillin & Dean* CLEAR	McMillin & Dean* PARTLY CLOUDY	Phillips† PARTLY CLOUDY	Phillips† CLOUDY	Phillips† ALL
1000-850	2.3°C.	2.5°C.	2.7 (2.5)°C.	2.4 (2.2)°C.	1.9 (1.6)°C.
850-700	1.9	2.3	2.2 (2.0)	2.3 (2.1)	
700-500	1.7	1.7	1.6 (1.2)	1.5 (1.1)	
500-400	2.3	2.0	2.0 (1.7)	2.2 (2.0)	
400-300	2.2	2.2	2.2 (2.0)	2.4 (2.2)	
300-200	2.2	2.2	2.0 (1.7)	1.9 (1.6)	
200-100	2.0	2.1	1.5 (1.1)	1.5 (1.1)	
100-70	1.7	1.8			1.6 (1.2)
70-50	2.2	2.1			2.0 (1.7)
50-30	2.3	2.0			

*RMS OF DIFFERENCES BETWEEN SATELLITES AND RADIOSONDES. ~3000 PAIRS, 30-60°N., 20 MAY - 2 JUNE 1980 BUT USING 1982 OPER. RETRIEVAL METHOD.

† $\sqrt{}$ OF ESTIMATED VALUES OF THE SQUARE OF SAT. ERROR PLUS SQUARE OF R/S ERROR. VALUES IN ( ) ASSUME RMS R/S ERROR OF 1.0°C. ONLY OCEAN RETRIEVALS, 30-60°N. 17-30 NOV. 1981 FOR 1000-100 MB + ALL NOV. FOR 100-30 MB FOR ALL RETRIEVALS (CLR, PTLY CLDY, CLDY).

Figure 9-5

- Evidence of short period (space + time) variability from frequent obs. of dense network of R/S ≈ 1.5°C.
- Reasonable estimate of R/S error ≈ 1.0°C.

o Phillips' data-base is better than operational:
- TOVS radiances interpolated in space to R/S location
- R/S interpolated in time to that of TOVS observation.
- Island and ship R/S stations only used in comparison.

* No parentheses includes R/S error.
In parentheses assumes 1°C RMS R/S error at all heights.

C. NEXT GENERATION - ADVANCED MICROWAVE SOUNDING UNIT (AMSU) -

o Remove cloud contamination for both temperature & H_2O.
o Increase vertical resolution.

(Specifications for AMSU were summarized in lecture 5.)

Figure 9-6 (Vu-graph) - Shows weighting functions for HIRS on current Polar Orbiters.

Figure 9-7 (Vu-graph) - Overlaid on Fig. 9-6, shows increased resolution in vertical of AMSU, especially above 200 mb.

MISSING

MISSING Figure 9-8 (Vu-graph) - Shows weighting functions for the four water vapor channels of AMSU.

III. Geostationary soundings by the VISSR Atmospheric Sounder.

A. Specifications for VAS were summarized in lecture 4.

✓ Figure 9-9 (slide) shows the weighting functions for VAS.
(channel 11 - yellow - is temp.)
Not as good as TOVS.

Fig. 9-6

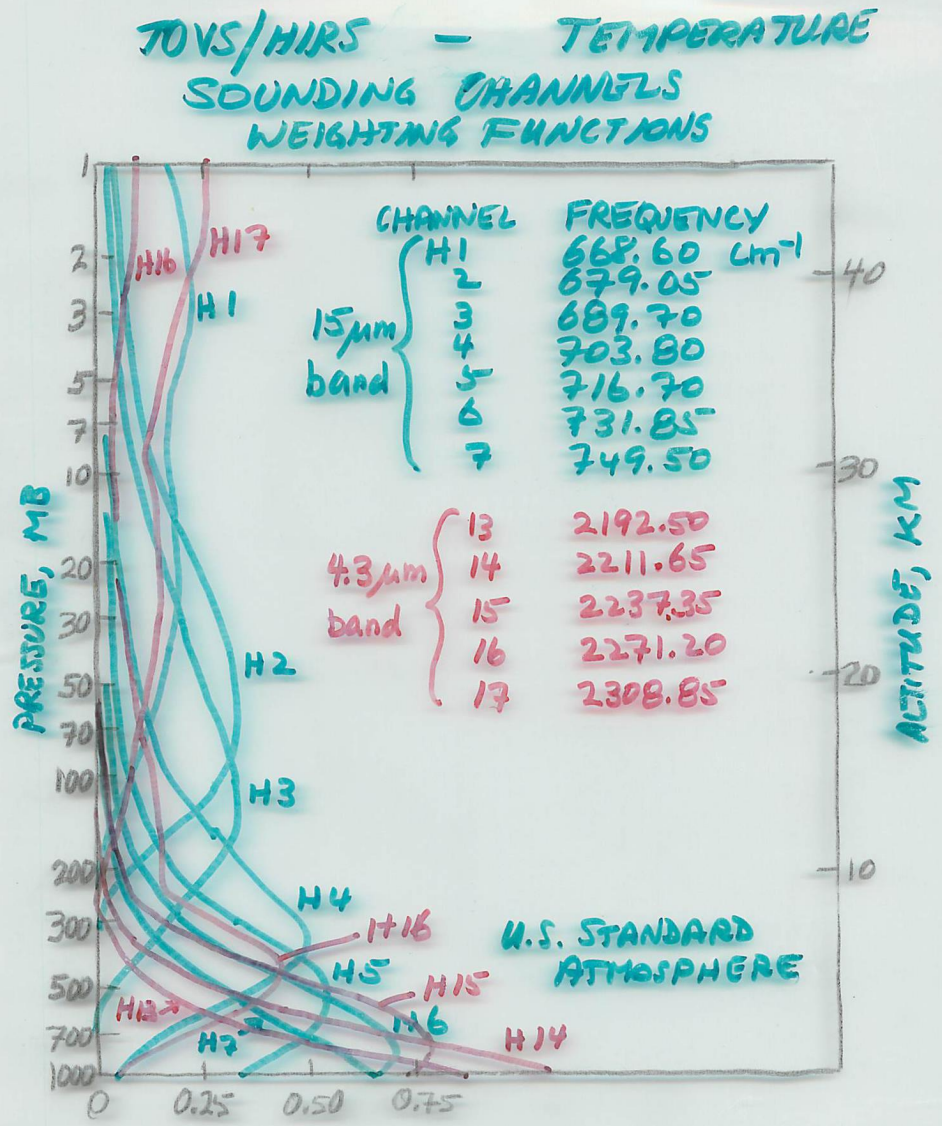


Figure 9-6

Vu-Graphs 9-7 and 9-8 Overlays

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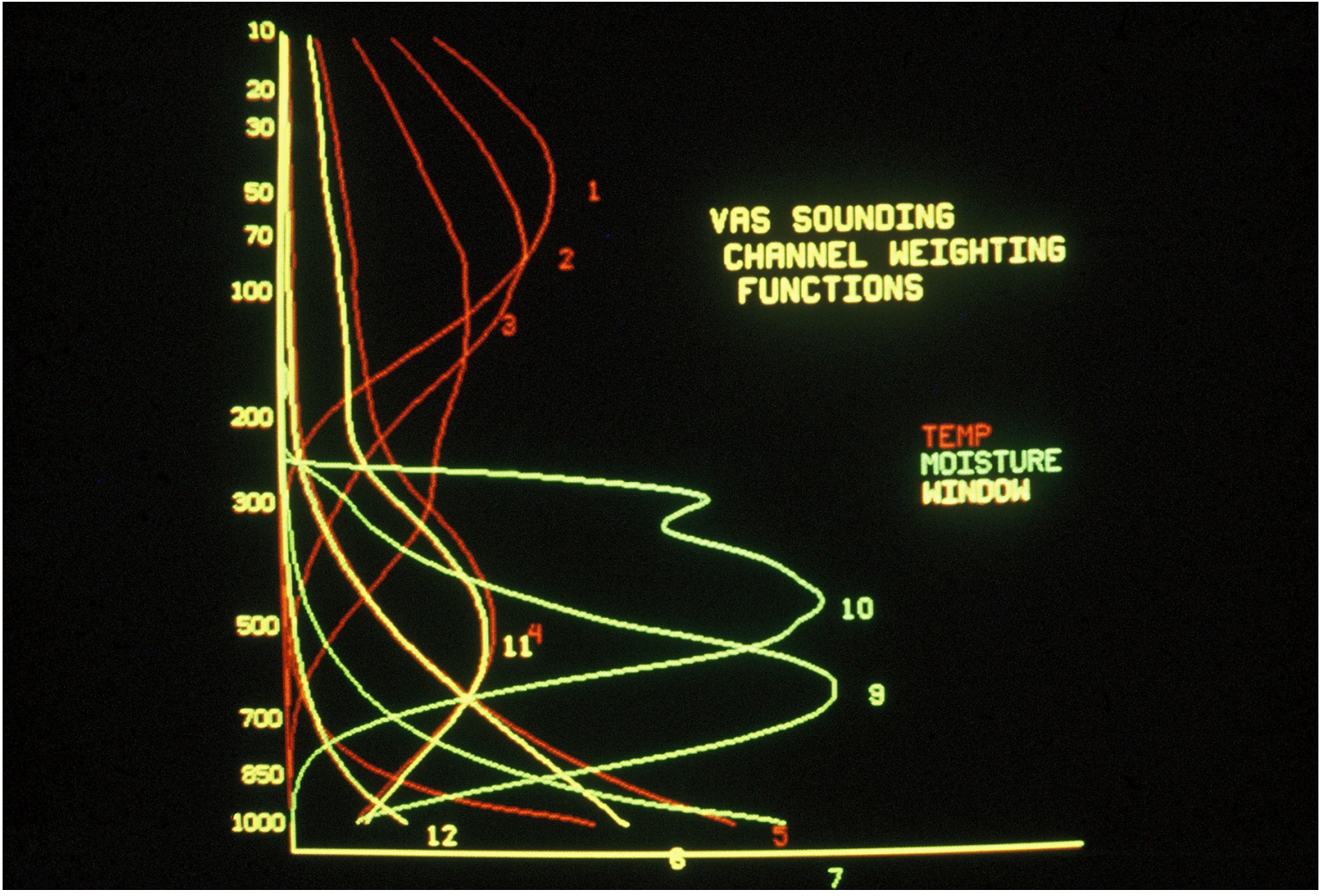
Fig. 9-9


VAS SOUNDING
CHANNEL WEIGHTING
FUNCTIONS
TEMP
MOISTURE
WINDOW
10
20
30
50
70
100
200
300
500
700
850
1000
1
2
3
4
5
6
7
8
9
10
11
12

B. VAS accuracy – No statistics available yet. Smith & Co. ~~indicate~~ state that comparisons between VAS and TOVS indicate they are "comparable".
- Big advantage of VAS is its time-resolution.

C. Examples of VAS results. (From McIDAS display)

1. VAS 700 MB TEMPS (x10); R/S 700 MB WINDS.
20 JULY 1981

✓ FIGURE 9-10 (slide) – Note difference in density of obs.

Processing procedure: Radiances from a "1st guess" temp. sounding calculated (climatology, NMC analysis, previous R/S or VAS sounding); compared to observed VAS radiances; 1st guess adjusted; etc., until computed and observed radiances agree within the noise level of the data. Each VAS sounding based on several adjacent fields of view which are checked to be free of cloud contamination (or corrected?) and are spatially averaged.

2. CHANGE IN 300 MB GRADIENT WIND FIELD; 3 HR INTERVALS.
↳ BASED ON VAS SOUNDINGS.

✓ Figure 9-11 (slide) – 20 JULY 1981.

NOTE increase in intensity during 9 hr. period.

✓ Figure 9-12 (slide) APPLICATION OF VAS TO SEVERE WX. FORECASTING.
20 JULY 1981.

BLUE: 300 MB. GRADIENT WIND SPEED COMPUTED FROM VAS.

YELLOW: 3-HOUR CHANGE IN PRECIPITABLE WATER

RED RECTANGLE: NSSFC ~~WATCH~~ SEVERE WEATHER WATCH Box.

COULD HAVE BEEN CUT IN HALF BY USE OF VAS (DRYING IN WESTERN HALF)

D. SOUNDING ON GOES-NEXT – Already discussed in lecture 5.
- Full time soundings independent of imaging mode.
- Increased channels (vertical resolution) and precision; should be comparable to TOVS (without microwaves)

Fig. 9-10

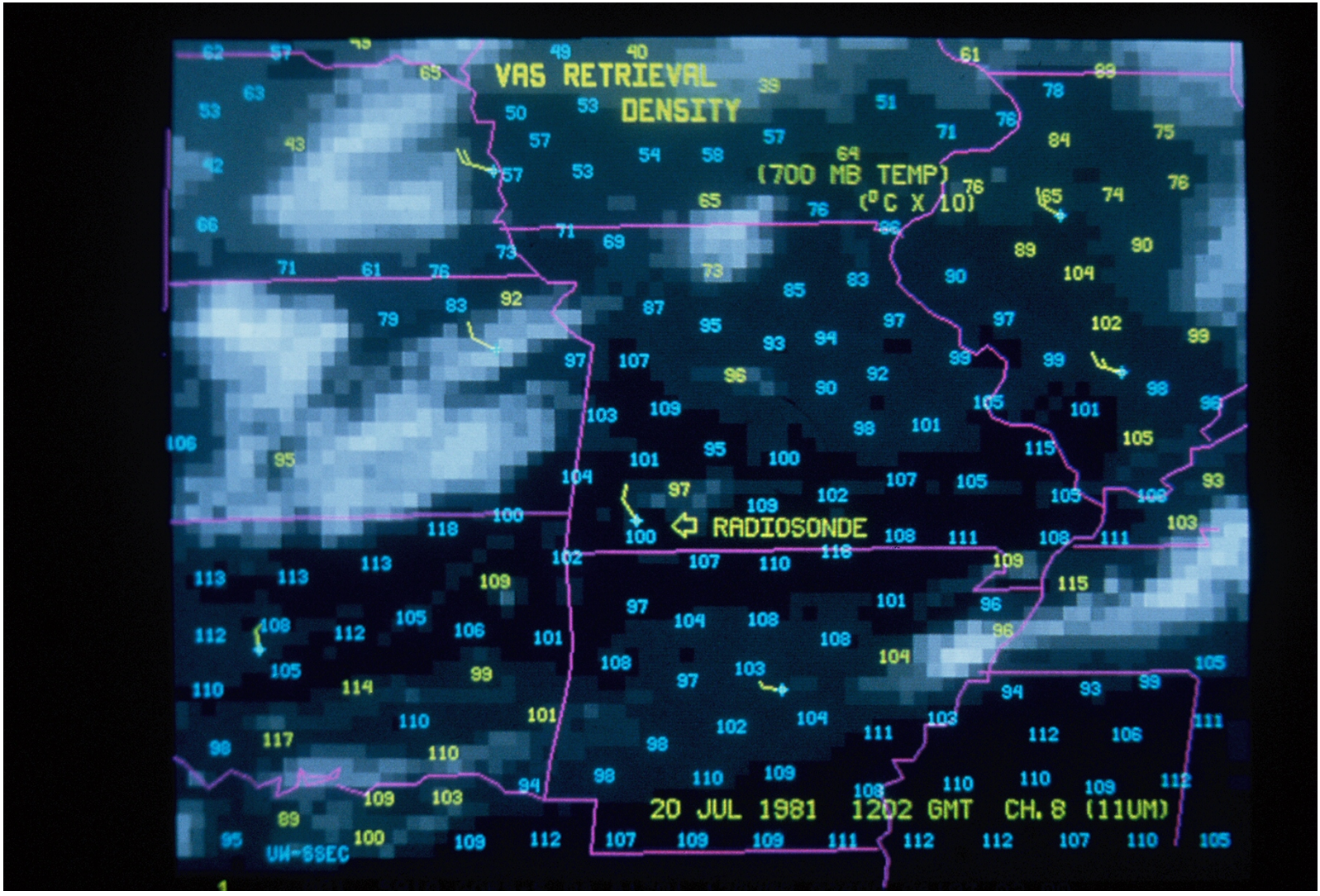

VAS RETRIEVAL
DENSITY
(700 MB TEMP)
(°C X 10)
RADIOSONDE
20 JUL 1981 1202 GMT CH.8 (11UM)
UW-SSEC

Fig. 9-11

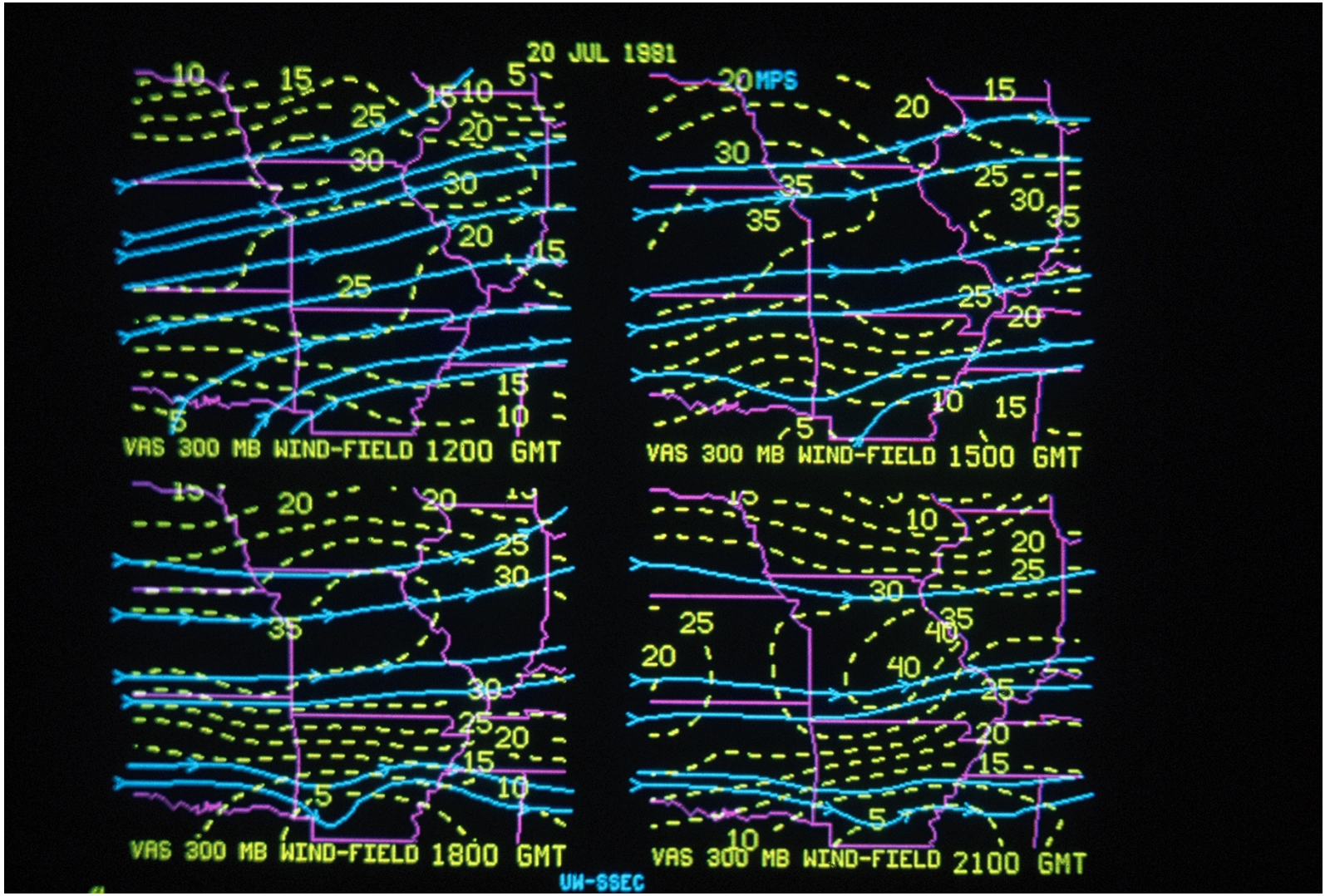
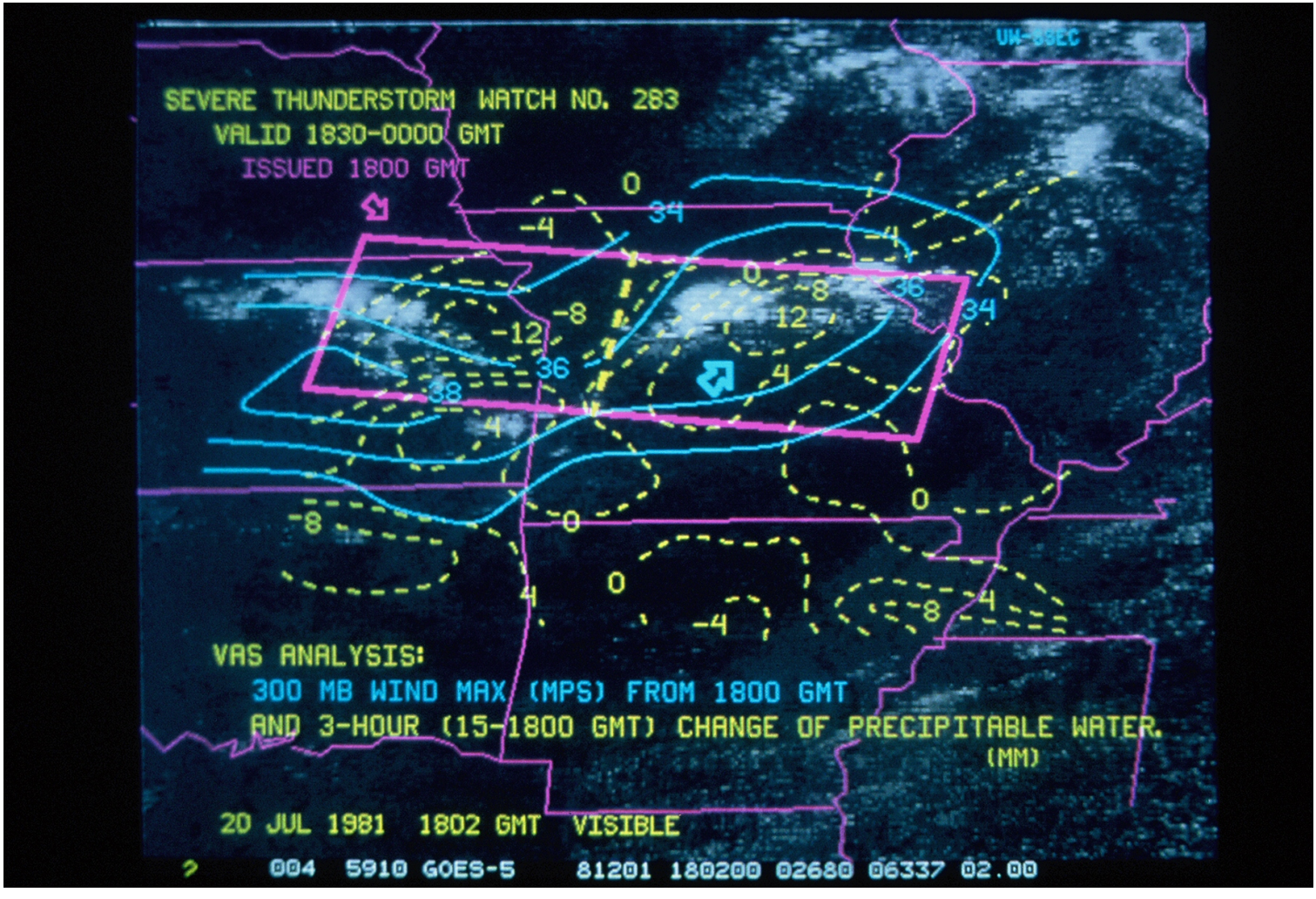

20 JUL 1981
MPS
VAS 300 MB WIND-FIELD 1200 GMT
VAS 300 MB WIND-FIELD 1500 GMT
VAS 300 MB WIND-FIELD 1800 GMT
VAS 300 MB WIND-FIELD 2100 GMT
UW-SSEC

Fig. 9-12


SEVERE THUNDERSTORM WATCH NO. 283
VALID 1830-0000 GMT
ISSUED 1800 GMT
VAS ANALYSIS:
300 MB WIND MAX (MPS) FROM 1800 GMT
AND 3-HOUR (15-1800 GMT) CHANGE OF PRECIPITABLE WATER.
(MM)
20 JUL 1981 1802 GMT VISIBLE
004 5910 GOES-5 81201 180200 02680 06337 02.00

IV. Postscripts

A. Retrieval methods.

- Currently use regression method based on R/S.
- Hope for purely physical method based on accurate knowledge of atmospheric transmittances as measured in lab. Hasn't been as accurate up until now. Recent effort by GSFC group shows very promising results; now being examined by NESS for operational applicability.
- Future role of R/S ?

B. Polar vs Geostationary.

Polar – global + probably always more accurate, esp. in clouds. input to NWP

Geostationary – Process for limited, critical weather areas as needed.

C. Improved vertical resolution ?

- limb measurements for stratosphere.
- For the troposphere ??
  - lasers?
  - limb μwave measurements?