# Introducing GOES-I: The First of a New Generation of Geostationary Operational Environmental Satellites

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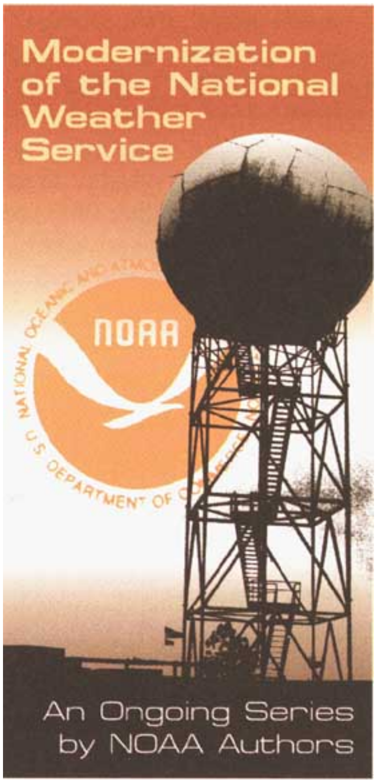
## Abstract

In the spring of 1994, the first of the National Oceanic and Atmospheric Administration's (NOAA's) next generation of geostationary satellites, GOES-I, is scheduled for launch. The introduction of this major component of NOAA's modernization represents a significant advance in geostationary remote sensing. All major components of the GOES-I system are new or greatly improved: 1) the satellite is earth oriented to improve instrument performance; 2) sounding and imaging operations are now performed by different and separate instruments; 3) a five-band multispectral radiometer with higher spatial resolution improves imaging capabilities; 4) a sounder with higher radiometric sensitivity enables operational temperature and moisture profile retrieval from geostationary altitude for the first time; 5) a different data format is used to retransmit raw data to direct-receive users; and 6) a new ground data processing system handles the high data volume and distributes advanced products to a variety of users.

This article describes the features of the GOES-I spacecraft and instruments, imaging and sounding schedules, data handling systems, and remote sensing products. Simulations of GOES-I imager and sounder products are presented and compared with *GOES-7* products. The simulations show that GOES-I imagery, derived product images, and sounder products should be significant improvements in both frequency of coverage and accuracy.



## 1. Introduction

### *a. GOES background*

Since the early 1960s, meteorological, hydrological, and oceanographic data from satellites have had a major impact on environmental analysis, weather forecasting, and atmospheric research in the United States and throughout the world. While polar-orbiting satellites provide snapshots of various phenomena once or twice daily, it was not until December 1966, when the National Aeronautics and Space Administration (NASA) launched the first geostationary Applications Technology Satellite (*ATS-1*), that the ability to see weather systems in animation was realized. *ATS-1* imaged the full-disk earth every half-hour with a spin scan camera conceived and designed by Verner Suomi (Suomi and Parent 1968). Operational use of *ATS-3* imagery at the National Severe Storm Forecast Center (NSSFC) and the National Hurricane Center (NHC) followed in 1972. NASA research and development fostered the Geostationary Operational Environmental Satellite (GOES) program within the National Oceanic and Atmospheric Administration (NOAA). Five spin stabilized satellites were built and launched, introducing a new era of satellite service: NASA's demonstration of two Synchronous Meteorological Satellites (SMS) began with the launch of *SMS-1* in May 1974 and NOAA's operation of a GOES series followed with the launch of *GOES-1* in October 1975. The Visible and Infrared Spin Scan Radiometer (VISSR) provided imagery from these original SMS and GOES satellites.

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In final form 17 February 1994.

GOES significantly advanced our ability to observe weather systems by providing frequent interval visible and infrared imagery of the earth surface, atmospheric moisture, and cloud cover. GOES data soon became a critical part of National Weather Service (NWS) operations by providing unique information about existing and emerging storm systems both day and night. Subsequently, more spectral bands were added to the VISSR, enabling the GOES system to acquire multispectral measurements from which atmospheric temperature and humidity sounding could be derived: the VISSR Atmospheric Sounder (VAS) was introduced on *GOES-4* in 1981. Although the addition of more spectral bands represented a major improvement in satellite capability, several compromises were necessary. First, imaging and sounding could not be done at the same time. Second, the spinning GOES–VAS viewed the earth only 5% of the time, so it was not possible to attain the instrument signal-to-noise ratios needed for either high-quality soundings or high spatial resolution image data. Thus, while the image data were used operationally, the sounding data were used only in special experiments. Recognizing the need for improved imaging and sounding, NOAA began development of its next generation of geostationary satellites, GOES I-M, in 1985.

### *b. GOES-I in 1994*

In the spring of 1994, the first of NOAA's next generation of geostationary satellites, GOES-I, is scheduled for launch. The GOES I-M system has been developed by Space Systems/Loral, under NASA supervision, for NOAA. ITT is the subcontractor for the GOES I-M imager and sounder instruments. Each GOES I-M spacecraft is designed for a five-year lifetime. The GOES I-M series introduces improved capabilities to observe weather-related phenomena on all scales from geostationary altitude and represents the evolution of geostationary satellite technology in the United States during nearly a quarter of a century. It supports most U.S. geostationary environmental satellite requirements, both operational and research, into the early twenty-first century.

Responding to user requirements for improvements in the GOES–VAS system, the GOES I-M system promises (a) no conflict between imaging and sounding operations, (b) multispectral imaging with improved resolution and better signal to noise in the infrared bands, (c) more accurate atmospheric temperature and moisture soundings, (d) more precise image frame-to-frame registration, and (e) stable long-term calibration. The GOES I-M imager improves operational multispectral imaging capability; the GOES I-M sounder allows NOAA to begin operational geostationary sounding for the first time.

With the GOES I-M series, there are new designs for all major portions of the system: (a) to improve instrument performance, the satellite is earth oriented—that is, three axes stabilized, so that the earth–atmosphere is observed nearly continuously; (b) to avoid conflicts between sounding and imaging operations, separate instruments perform those functions; (c) to improve imaging capabilities for cloud and storm diagnostics and to enhance signal-to-noise characteristics for atmospheric sounding, new multispectral sensors were designed; (d) to accommodate constant earth observation, a different data format was devised for retransmission of raw data to direct-receive users; and (e) to handle the high data volume, a new ground data processing system was developed to distribute data and products to a variety of users.

In addition to the customary DCP (data collection platform) and SEM (space environment monitoring) services, the satellite has an improved WEFAX (weather facsimile) capability. It also provides dedicated SAR (search and rescue) support from geostationary altitude for the first time.

The earth-oriented spacecraft design (see Fig. 1) required new scanning, navigation, calibration, and thermal control systems. For more efficient imaging

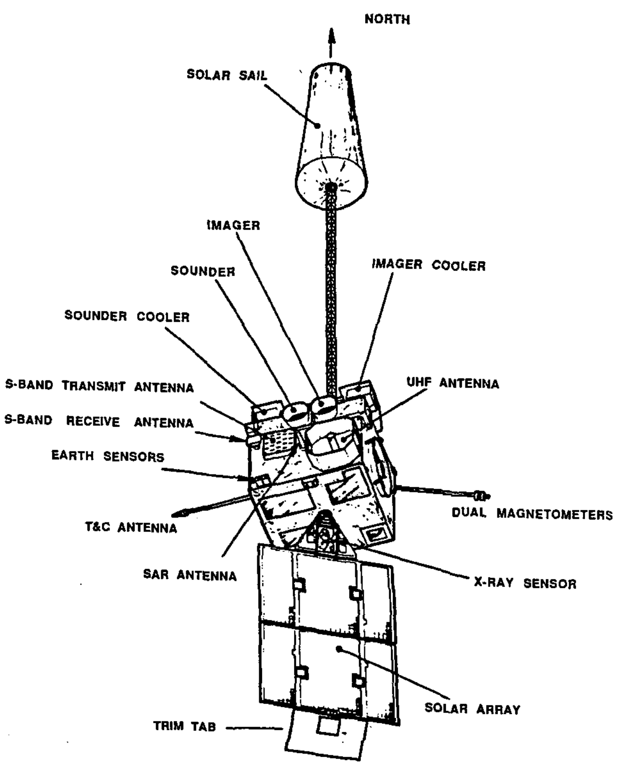

FIG. 1. Spacecraft on orbit configuration. The main body is 78 in. × 84 in. × 92 in., and the overall length is 96 ft, of which the solar sail boom constitutes 58 ft.

with near-continuous viewing of the earth, the scanning system moves in boustrophedon fashion, slewing back and forth east to west and then west to east; GOES–VAS sampling is always west to east. A "star sensing" system allows precise pointing of the imager and sounder systems; thus, pixels are located to within 4 km at nadir. Image and mirror motion compensation systems correct for satellite and instrument motions that affect image frame-to-frame registration. Improved navigation and gridding allow images to be presented in a fixed GOES projection. To improve calibration, reference blackbodies are external to the instrument telescopes so that space and blackbody looks are used directly to convert detector response into radiances; on the GOES–VAS, an internal blackbody offers less precise calibration because it requires adjustment for the stray radiation from the telescope optics in front of the blackbody. To accommodate the large daily thermal changes that occur with staring instruments, increased monitoring of thermal gradients and telescope focal properties is introduced.

The following sections describe various features of the GOES I-M spacecraft, data handling system, and products. The satellite sensor systems are discussed in section 2. Quality control procedures for converting data into products follow in section 3. WEFAX, DCP, SEM, and SAR services are presented in section 4. Section 5 outlines data flow to the users, probable imager and sounder schedules, and initial product suites. Section 6 presents some examples of simulated GOES-I imager and sounder data. Finally, section 7 looks at potential future products and services.

## 2. Meteorological sensor systems on GOES I-M

The earth-oriented GOES I-M enables more efficient data gathering by both the imager and sounder; both yield higher spatial resolution and improved signal-to-noise over that available previously. The separate instruments for sounding and imaging allow full use of both capabilities. The imager and sounder have generally common features (Table 1), although there are some differences (Savides 1992). Specifics concerning each are presented in sections 2a and 2b.

### *a. Imager*

The GOES I-M imager has a five-band multispectral capability with high spatial resolution. This enables improvement in present services and allows for the development of a number of advanced products. The five spectral bands are (a) 0.52–0.72 $\mu$m (visible), (b) 3.78–4.03 $\mu$m (shortwave infrared window), (c) 6.47–7.02 $\mu$m (upper-level water vapor), (d) 10.2–11.2 $\mu$m (longwave infrared window), and (e) 11.5–12.5 $\mu$m (infrared window with slightly more sensitivity to water vapor than the other infrared windows). In comparison, the GOES–VAS imaging mode includes data from one or two atmospheric sounder spectral bands to accompany the routinely available visible and 11.2-$\mu$m infrared data (Smith et al. 1981). Among the VAS spectral bands frequently included in that multispectral data stream are those centered on 13.3, 12.7, 7.3, 6.7, and 3.9 $\mu$m. The GOES I-M imager band selections were in part patterned after the Advanced Very High Resolution Radiometer (AVHRR) carried on the NOAA polar-orbiting satellites and in part dictated by the need for continuity of GOES–VAS spectral capabilities. Desired noise characteristics were specified based on experience with the AVHRR and GOES–VAS data and current detector technology.

The GOES I-M imager provides visible data with about 1-km resolution as GOES–VAS but with a stable linear response and 10-bit precision (1 part in 1024), improving upon the GOES–VAS variable nonlinear 6-bit response (1 part in 64). By using star positions in addition to traditional landmarks, imagery is earth navigated within 2–4 km compared to 3–10 km with GOES–VAS. The GOES I-M imager provides infrared imagery simultaneously in four thermal bands instead of the two or three bands available in the imaging mode from GOES–VAS. For nadir view, the imager's infrared window bands are at 4-km horizontal resolution (water vapor band is at 8 km), while the GOES–VAS infrared window band is at 6.9 km (other bands are at 13.8 km). Onboard calibration provides brightness temperatures with 1.0-K absolute accuracy and 0.3-K relative precision, and noise levels reduced two to three times over GOES–VAS. Table 2 compares expected GOES-I imager characteristics with that of the current GOES–VAS, *GOES-7*.

The detector instantaneous geometric field of view (IGFOV) or footprint and a derived sampled subpoint resolution (SSR) are presented in Table 2. SSR modifies IGFOV by accounting for instrument response (Gabriel and Purdom 1990) and sampling rate. GOES-I oversamples infrared IGFOVs, 4 and 8 km, along a scan line by factors of 1.75 and 3.5, respectively; the 1-km visible IGFOV is oversampled by a factor of 1.75. *GOES-7* oversamples infrared IGFOVs, 6.9 and 13.8 km, along a scan line by factors of 2.3 and 4.6, respectively; the 0.8-km visible IGFOV is sampled contiguously without oversampling.

The visible band, upper-level water vapor band centered at 6.7 $\mu$m, and longwave window band centered at 10.7 $\mu$m on GOES-I are familiar to most GOES–VAS users through their depiction of the earth

Table 1. Imager and sounder instrument features.

| Feature | Imager | Sounder |
|---|---|---|
| Optical aperture | 31.1 cm | 31.1 cm |
| Type optics | Cassegrain | Cassegrain |
| Methods of scan | Two axes, continuous<br>Linear E/W 64 $\mu$rad (2.3 km)<br>Line step N/S 224 $\mu$rad (8 km) | Two axes, step and dwell<br>E/W 280-$\mu$rad steps<br>N/S 1120-$\mu$rad steps<br>(or 2240-$\mu$rad with 0.1- or 0.2-s dwell) |
| Spatial resolution | Visible 28 $\mu$rad (1 km)<br>IR windows 112 $\mu$rad (4 km)<br>$H_2O$ band 224 $\mu$rad (8 km) | 242 $\mu$rad (10 km) |
| Sampling | Visible 1.75/IGFOV*<br>IR windows 1.75/IGFOV<br>$H_2O$ band 3.5/IGFOV | Four IGFOVs sampled at the same time |
| Sampling rate | 20° $s^{-1}$<br>183.3 $\mu$sec per pixel (IR)<br>45.8 $\mu$sec per pixel (vis) | 40 soundings $s^{-1}$<br>0.1, 0.2, or 0.4 s per sample |
| Spectral band coregistration | ±28 $\mu$rad | Within 22 $\mu$rad of IR 10.7-$\mu$m window |
| Data output | 10-bit quantization | 13-bit quantization |
| Data rate | 2.6208 Mb $s^{-1}$ | 40 kb $s^{-1}$ |
| Time between space looks | 2.2 s<br>(nominally for large frame)<br>9.2 or 36.6 s<br>(nominally for small frame) | 2 min |
| Time between blackbody calibrations | 10–30 min | 20 min |

*Instantaneous geometric field of view

surface in clear sky, clouds, and upper-tropospheric moisture. GOES-I images in these bands are noticeably sharper through the improved quantization in the visible band and the improved signal to noise and higher spatial resolution in the infrared bands. The band centered at 3.9 $\mu$m is useful for the identification of fog at night (Ellrod 1992), discriminating between water clouds and snow or ice clouds during the daytime (Scorer 1989), detecting fires (Prins and Menzel 1992) and volcanoes, and determining nighttime sea surface temperature (Bates et al. 1987). The longwave window band centered at 10.7 $\mu$m and the split window band centered at 12.0 $\mu$m in combination are useful for identification of low-level moisture (Chesters et al. 1987), determination of sea surface temperature, and detection of airborne dust and volcanic ash. Differences in emissivity in the GOES-I infrared bands should lead to the development of a variety of applications, especially at night, when the 3.9-$\mu$m band can be used without visible light contamination. Table 3 highlights some anticipated improvements in GOES-I imager products. Section 6 presents simulations of GOES-I imagery and comparisons with imagery from *GOES-7.*

### *b. Sounder*

The GOES I-M sounder has 18 thermal infrared bands plus a low-resolution visible band, compared to the 12 infrared bands plus a visible band on GOES–VAS. The new spectral bands, at wavelengths never obtained before in geosynchronous orbit, are sensitive to temperature, moisture, and ozone. The GOES I-M sounder's design goal, like the imager's, is to provide brightness temperatures with 1.0-K absolute accuracy and 0.3-K relative precision. Table 4 summarizes the spectral band performance characteristics for the *GOES-7* and the GOES-I sounders. The full-time availability of the GOES-I sounder enables operational sounding products for the first time; this has the potential for contributing significantly to mesoscale forecasting over the conterminous United States, monitoring thermal winds over oceans, and supplementing the Automated Surface Observing System (ASOS) with upper-level cloud information.

The GOES I-M sounders will also allow for the development of a number of advanced products.

Figure 2 shows the GOES-I sounder spectral bands together with a depiction of the earth-emitted spectra; the carbon dioxide ($CO_2$), moisture ($H_2O$), and ozone ($O_3$) absorption bands are indicated. Around the broader $CO_2$ and $H_2O$ absorption bands, vertical profiles of atmospheric parameters can be derived. Sampling the center of the absorption band yields radiation from the upper levels of the atmosphere (e.g., radiation from below has already been absorbed by the atmospheric gas). Sampling away from the center of the absorption band yields radiation from successively lower levels of the atmosphere. In the wings of the absorption band are the windows that view to the bottom of the atmosphere. Thus, as a spectral band is moved toward the center of the absorption band, the radiation brightness temperature decreases due to the decrease of temperature with altitude in the lower atmosphere. GOES-I selection of spectral bands in and around the $CO_2$ and $H_2O$ absorbing bands is designed to yield information about the vertical structure of atmospheric temperature and moisture.

Table 2. *GOES-7* and GOES-I imager characteristics. IGFOV at nadir and SSR are presented in kilometers, and noise-equivalent temperatures for the thermal bands are specified for nominal scene temperatures (300 K for the window bands and 230 K for the water vapor band).

| Wavelength ($\mu$m) | IGFOV (km) E/W x N/S | SSR (km) E/W x N/S | Noise |
|---|---|---|---|
| ***GOES-7*** | | | |
| 0.55–0.75 | 0.75×0.86 | 0.75×0.86 | 6-bit data ± 2 counts 3 $\sigma$ |
| 3.84–4.06 | 13.8×13.8 | 3.0×13.8 | 0.25 K @ 300 K, 6.00 K @ 230 K |
| 6.40–7.08 | 13.8×13.8 | 3.0×13.8 | 1.00 K @ 230 K |
| 10.4–12.1 | 6.9×6.9 | 3.0×6.9 | 0.10 K @ 300 K, 0.20 K @ 230 K |
| 12.5–12.8 | 13.8×13.8 | 3.0×13.8 | 0.40 K @ 300 K, 0.80 K @ 230 K |
| **GOES-I** | | | |
| 0.52–0.72 | 1.0×1.0 | 0.57×1.0 | 10-bit data ± 8 counts 3 $\sigma$ |
| 3.78–4.03 | 4.0×4.0 | 2.3×4.0 | 0.15 K @ 300 K, 3.50 K @ 230 K |
| 6.47–7.02 | 8.0×8.0 | 2.3×8.0 | 0.30 K @ 230 K |
| 10.2–11.2 | 4.0×4.0 | 2.3×4.0 | 0.20 K @ 300 K, 0.40 K @ 230 K |
| 11.5–12.5 | 4.0×4.0 | 2.3×4.0 | 0.20 K @ 300 K, 0.40 K @ 230 K |

Table 3. Anticipated immediate improvements in GOES-I imager products.

- More details in imagery (4-km IR resolution, oversampled visible, better signal to noise, higher bit depth).
- Improved composite imagery (five spectral bands).
- Low-light visible imagery (10-bit visible data).
- Better synchronization with other observations (separate imager).
- Better cloud-drift winds (4-km resolution, better edge distinction).
- Improved water vapor motion (winds in clear regions).
- Enhanced severe storm forecasting (timely rapid imaging, derived products at 4 km, 10-bit visible data).
- Timely fog detection at night (continuous 3.9-$\mu$m imaging).

Initially, the GOES I-M sounder spectral selection was primarily patterned after the High-resolution Infrared Radiation Sounder (HIRS) carried on the NOAA polar-orbiting satellite, which has six bands in the 15-$\mu$m (longwave) band, a split-window pair, two midtropospheric water-sensitive bands (midwave), three 4-$\mu$m (shortwave) bands, and a visible measurement. Noise characteristics were specified based on experience with the HIRS and current detector technology. Subsequently, the sounder was expanded to 18 infrared bands, adding the ozone band and a number of additional shortwave bands (improving low-level vertical resolution), changing the longwave window arrangement to a more accurate split window, expanding the moisture-sensing bands from two to three, and adding a surface-sensing band. These changes were designed to improve vertical resolution for moisture sounding. Table 5 highlights the anticipated improvements in GOES I-M sounder products. Section 6 presents simulations of GOES-I soundings and derived products.

## 3. GOES I-M data quality control

Effective use of the GOES I-M imager and sounder data is accomplished by rigorous quality control pro-

TABLE 4. Sounder radiometer spectral channels, bandwidths, and noise equivalent radiance performance characteristics (NEDR in mW ster$^{-1}$ m$^{-2}$ cm). The *GOES-7* results are from evaluations of in-flight performance. The GOES-I results are from the prelaunch thermal vacuum tests; the range of values encompasses the four detectors used to detect the spectral radiation. The fourth column gives the conversion factor (CF) to convert from NEDR to noise equivalent temperature (NEDT) at 290 K; NEDT = (NEDR) (CF). The final column indicates the primary purpose of this band.

| | **Center wavelength $\mu$m (wavenumber cm$^{-1}$)** | ***GOES-7* NEDR (bandwidth cm$^{-1}$)** | **GOES-I NEDR (bandwidth cm$^{-1}$)** | **Conversion factor to NEDT (for 290 K)** | **Purpose** |
|---|---|---|---|---|---|
| **Longwave** | 14.71(680) | 5.40 (10) | 1.44–2.42 (13) | 0.624 | Stratosphere temperature |
| | 14.48(691) | 2.60 (16) | n/a | 0.621 | |
| | 14.37(696) | n/a | 1.23–1.60 (13) | 0.620 | Tropopause temperature |
| | 14.25(701) | 2.30 (16) | n/a | 0.619 | |
| | 14.06(711) | 1.60 (20) | 0.88–1.13 (13) | 0.616 | Upper-level temperature |
| | 13.96(733) | n/a | 0.75–0.92 (16) | 0.612 | Midlevel temperature |
| | 13.37(748) | 1.60 (20) | 0.74–0.77 (16) | 0.610 | Low-level temperature |
| **Window** | 12.66(790) | 1.30 (20) | 0.27–0.39 (30) | 0.610 | Total PW |
| | 12.02(832) | n/a | 0.16–0.23 (50) | 0.615 | Surface temp., moisture |
| | 11.03(907) | 0.14 (140) | 0.10–0.15 (50) | 0.638 | Surface temperature |
| **Ozone** | 9.71(1030) | n/a | 0.13–0.24 (25) | 0.718 | Total ozone |
| **Water vapor** | 7.43(1345) | n/a | 0.09–0.18 (55) | 1.18 | Low-level moisture |
| | 7.25(1377) | 1.30 (40) | n/a | 1.24 | |
| | 7.02(1425) | n/a | 0.06–0.12 (80) | 1.40 | Midlevel moisture |
| | 6.73(1487) | 0.33 (150) | n/a | 1.60 | |
| | 6.51(1535) | n/a | 0.08–0.13 (60) | 1.79 | Upper-level moisture |
| **Shortwave** | 4.57(2188) | n/a | 0.005–0.008 (23) | 11.10 | Low-level temperature |
| | 4.52(2210) | 0.030 (45) | 0.004–0.006 (23) | 11.89 | Midlevel temperature |
| | 4.45(2245) | 0.040 (40) | 0.004–0.007 (23) | 13.08 | Upper-level temperature |
| **Nitrogen** | 4.13(2420) | n/a | 0.002–0.003 (40) | 23.45 | Boundary-layer temperature |
| **Window** | 3.98(2513) | n/a | 0.002–0.004 (40) | 31.99 | Surface temperature |
| | 3.95(2535) | 0.008 (140) | n/a | 34.06 | |
| | 3.74(2671) | n/a | 0.001–0.004 (100) | 45.56 | Surface temp., moisture |
| **Visible** | 0.94(14367) | n/a | n/a | n/a | Cloud |

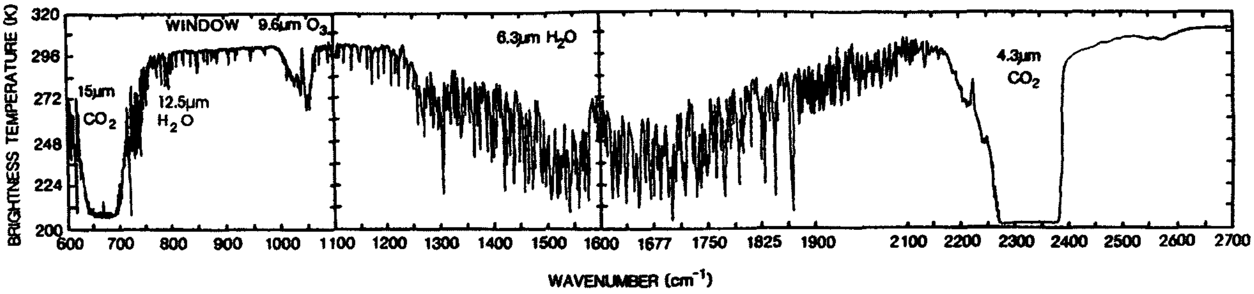

FIG. 2. Infrared portion of the earth–atmosphere-emitted spectra is shown on top. Brightness temperatures are plotted as a function of wavenumber. The GOES-I sounder spectral bands (and bandwidths) are indicated below. Qualitative indication of spectral band sensitivity to a given level of the atmosphere is also noted (stratosphere; high, middle, and low troposphere; earth surface).

cedures. This section discusses the backbone of the quality control system: navigation, registration, and calibration. Those functions are performed in real time to ensure utility of GOES I-M data for short-term warning and forecast.

One of the major challenges for the GOES I-M series was to develop a navigation system that would improve earth location and registration accuracy. That involved maintaining a stable imaging platform in a three-axes satellite environment and predicting image shifts due to orbital motion as well as instrument motion and thermal distortion. More details are available in Kelly (1989).

### *a. Navigation*

Image navigation refers to accurate earth location (latitude/longitude) of each pixel within an image. This requires precise knowledge of the spacecraft's position in the orbit and attitude within that orbit at the time of image acquisition. The spacecraft's position is determined as a function of time (orbit) as well as the orientation of the imager and sounder reference optical axis (roll, pitch, and yaw) with respect to the reference orbital axis (attitude). Three types of observations are obtained to determine orbit and attitude: stars, landmarks, and range. Those observations are processed on the ground in the Sensor Processing System (SPS) and Product Monitor (PM) and are then transmitted to the Orbit and Attitude Tracking System (OATS), where the actual calculation is performed (Kelly 1989).

Star measurements are obtained by pointing the instrument just east of a star's predicted position and waiting while the star crosses the instrument field of view; a typical detectable star diameter is 23 $\mu$rad, and its apparent movement is 72 $\mu$rad s$^{-1}$. Separate star-sensing capability exists in the imager and the sounder. The star's actual position is processed in the SPS and passed on to the OATS. It is anticipated that three star measurements with good geometric separation will be

TABLE 5. Anticipated improvements in GOES-I sounder products.

- Full-time coverage.
- Better synchronization with other observations (separate sounder).
- Better temperature and moisture soundings (better signal to noise from three-axes stable system).
- Hourly continental U.S. moisture and atmospheric stability.
- Better depiction of boundary layer (low atmospheric temperature and moisture with shortwave bands).
- Better numerical weather forecasting (better data accuracy and coverage in data-sparse areas and times).
- Hourly supplement to ASOS (with cloud information above 12 000 ft).
- Higher quality thermal gradient winds over oceans for numerical weather prediction models (especially for hurricane trajectory models).

obtained every half-hour without any significant impact on imaging operations. This should provide sufficient input data to determine daily attitude profiles.

Landmark measurements are made by locating geographic features of known latitude/longitude in the imager data. The imager line/pixel associated with a latitude/longitude is then sent to the OATS for input to the orbit determination process. This landmarking function is performed semiautomatically using cross-correlation techniques in the PM. While imager visible data is the primary source for landmarks, they can also be obtained from imager IR and sounder visible data. Landmarks are obtained in an off-line manner and therefore have little impact on operations. One landmark will be obtained per hour; more may be processed depending on operational needs.

Range is estimated in the SPS by measuring the elapsed time between the uplink and downlink signal of the retransmitted data. The SPS formulates a range measurement for OATS input. A range measurement is performed every half-hour.

TABLE 6. Image navigation and registration performance requirements (indicated to 3 $\sigma$). Requirements are relaxed near midnight to accommodate the impact of solar heating on the instruments.

| Parameter | Noon (±8 h) | Midnight (±4 h) |
|---|---|---|
| **Imager** | | |
| Nadir navigation accuracy | 4 km | 6 km |
| Registration (within 25-min image) | 42 $\mu$rad (1.5 km) | 42 $\mu$rad (1.5 km) |
| Registration (between repeated images) | | |
| 15 min | 42 $\mu$rad (1.5 km) | 70 $\mu$rad (2.5 km) |
| 90 min | 84 $\mu$rad (3 km) | 105 $\mu$rad (3.75 km) |
| 24 h | 168 $\mu$rad (6 km) | 168 $\mu$rad (6 km) |
| 48 h | 210 $\mu$rad (7.5 km) | 210 $\mu$rad (7.5 km) |
| Coregistration (band to band) | 28 $\mu$rad (1 km) | 28 $\mu$rad (1 km) |
| Fixed grid duration | 24 h | 24 h |
| **Sounder** | | |
| Nadir navigation accuracy | 10 km | 10 km |
| Registration (within 120-min sounding) | 84 $\mu$rad (3 km) | 112 $\mu$rad (4 km) |
| Registration (between repeated soundings) | | |
| 24 h | 280 $\mu$rad (10 km) | 280 $\mu$rad (10 km) |
| Coregistration (w.r.t. to band 8) | 22 $\mu$rad (0.78 km) | 22 $\mu$rad (0.78 km) |

### *b. Registration*

Registration refers to controlling the instrument so that each pixel defines the same earth location in successive images within a certain error budget over a 24-h period. This is accomplished using two systems: image motion compensation (IMC), and mirror motion compensation (MMC).

IMC and MMC continuously correct imager and sounder pointing for deterministic orbit and attitude effects and for the effect on satellite attitude induced by the scan and slew motions of the instrument themselves. These two corrections together are intended to produce images registered within the performance requirements summarized in Table 6.

The IMC models, and then removes, orbit and attitude motion from each image. Coefficients that describe the orbit and attitude contribution to pixel shifts are generated in the OATS and uplinked to the spacecraft. These coefficients are applied in an orbit and attitude model in the onboard attitude and orbit control electronics (AOCE), which computes correction signals at a rate of 64 per second. These signals are applied to the azimuth and elevation servomotors of the imager and sounder, and compensate for the predicted orbit and attitude motion. For example, if perturbations to optical axis motion due to orbit and attitude motion were predicted to be in the southeast direction, correction signals would be generated in the northwest direction. This produces an image with no apparent motion. Through this process each subsequent image is registered to the previous image within error tolerances (Table 6).

In addition to IMC, a second correction signal is applied to the instrument to enhance registration accuracy. The GOES I-M imager and sounder scan mirrors operate independently. While one instrument is scanning, the other could be slewing for star sensing, a space look, or performing blackbody calibrations. The scan and slew motion of one instrument affects the spacecraft attitude and hence the pointing of the other scanning instrument in a predictable fashion. This second correction, MMC, is automatically generated by separate control logic in the AOCE. The compensation signal is generated at the onset of scanner motion in one instrument and applied to the scanner servomotor of the other instrument. These corrections are applied continuously and are independent of ground operation.

The IMC system references all images to a perfect GOES projection. This projection (defined by satellite subpoint) is input to the IMC coefficient generation process in the OATS. The OATS then computes coefficients that produce images earth located and registered to this standard grid over the period that the coefficients are in effect. The "fixed gridding" allows gridding information to be generated once in a 24-h period. The IMC process fits the images to this standard grid. NOAA plans to use this capability so that all images are referenced to a standard grid centered over the equator at the nominal satellite subpoint. IMC biases all images to this "perfect GOES projection"; the grid is generated once per day at the implementation of a new IMC set on board the spacecraft. Plans are to maintain this projection within the navigation specifications except when the satellite is being moved from one station to another or when the satellite inclination increases beyond 2° near the end of the mission.

The capability to maintain one GOES projection significantly simplifies user earth location. Since the gridding information is generated only once per day, the user also needs to generate earth location information only once per day, at the implementation of a new IMC set. This earth location information is accurate within specified error tolerances (see Table 6) from image to image for the ensuing 24-h period.

### *c. In-flight infrared calibration and visible normalization*

Calibration of the GOES I-M imagers and sounders is a multistage process beginning before satellite launch and extending throughout the lifetime of the instruments. Before launch, instrument calibration is characterized in tests under controlled conditions. In flight, the infrared bands are calibrated from data taken when the instruments view space and an onboard blackbody. Calibration is applied to scene data in real time in the SPS computer at the Wallops Island, Virginia, command and data acquisition (CDA) station. Visible data are normalized at the same time. Thevisible channels cannot be calibrated in flight, because the GOES I-M satellites do not carry calibrated sources of visible radiation. See Weinreb (1989) for more details.

#### 1) VISIBLE NORMALIZATION

Each GOES I-M imager has eight visible channels, while each sounder has four. Eight silicon photodiode detectors in the imager focal plane produce data for eight scan lines simultaneously as the mirror scans. Each sounder has four such detectors, which simultaneously produce four scan lines of data.

After ground processing of the spacecraft signal, visible channel data are transmitted to users as digital count values with 10 bits of information for the imager and 13 bits for the sounder. The data stream contains calibration coefficients for users wishing to convert count values to radiances and albedos. Those coefficients are determined before launch with an integrating sphere whose calibration is traceable to the National Institute of Standards and Technology. After launch, the validity of that calibration is uncertain since it is possible that the sensor gains may change.

As with the present GOES instruments, the visible data from the imager are normalized to compensate for differences in gain among the eight channels (Weinreb et al. 1989). Sounder visible data are normalized separately. The data are normalized in the SPS at Wallops in real time with 10-bit conversion tables for the imager and 13-bit conversion tables for the sounder. This is done by relating the raw radiance outputs, in digital counts, to normalized ones. Striping should be less of a problem for GOES I-M than it is with the present GOES because of the finer quantization of the GOES I-M intensity scales.

The silicon photodiode detectors used in GOES-I have been proven to be more stable over time than the photomultiplier tubes used in the GOES–VAS; thus, a single set of normalization tables should be valid for months at a time. The normalization tables are generated off-line at the National Environmental Satellite Data and Information Service (NESDIS) in Suitland, Maryland, by matching of empirical distribution functions (Weinreb et al. 1989). The basic idea is that with a large ensemble of measurements the distribution of intensity measurements in every channel should be the same. One channel is designated as a reference channel, and the outputs of other channels are modified, so their intensity distributions are the same as that of the reference channel. The reference channel is chosen so that its observations fill as much of the range of digital counts as possible without clipping at either the low or high ends. Even more important, the reference channel should have a stable gain that does not change rapidly with time.

#### 2) INFRARED CALIBRATION

Each GOES I-M imager has two infrared channels for the bands centered at 3.9, 10.7, and 12.0 $\mu$m, and one channel for the band centered at 6.7 $\mu$m; each sounder has four channels for each of the 18 infrared bands. Two (or one for the water vapor channel) infrared detectors in the imager focal plane produce data for two (or one) scan lines simultaneously. Each sounder has four such detectors that simultaneously produce four scan lines of data. As with the visible channels, infrared channel data are transmitted to users as digital count values with 10 and 13 bits of information for the imager and sounder, respectively.

The infrared channels are calibrated in real time from data acquired in flight when the sensors view space and onboard warm blackbodies. The onboard blackbodies are external to the entire optical trains of both the imager and the sounder and fill their aperture; this procedure allows a full-system calibration rather than the partial calibration of the GOES–VAS, where the radiation from the blackbody calibration source bypasses the telescope.

The calibration equation, which relates sensor output $x$ (in digital counts) to scene radiance $R$, is

$$R = qx^2 + mx + b.$$

The coefficients $m$ and $b$ are the slope and intercept, respectively. The quadratic term (with coefficient $q$) corrects for possible nonlinearities in sensor response, which may occur with the channels using mercury cadmium tellurium (HgCdTe) detectors.

The current GOES satellites, which spin at 100 rpm, experience small diurnal temperature excursions. However, since the GOES I-M satellites are three-axes stabilized, temperatures within the sensors vary by tens of degrees Kelvin over a 24-h period. Therefore, the coefficients in the calibration equation must be updated frequently. To accomplish this, both the imager and the sounder view space routinely (see Table 1). The sounder views its blackbody every 20 min, while the imager normally views its blackbody every 10 min unless doing so interrupts an image in process. At the most, the imager operates 30 min between blackbody views—for example, when it makes a full-disk image. Drift in detector response [often referred to as "1/*f* noise" (Bak et al. 1987)] dictates that the space and blackbody calibration looks occur frequently enough to keep changes in calibration within the specified noise levels. The ground system processing interpolates between calibration events, so that different calibration coefficients are determined for each data sample to account for the linear portion of the detector drift.

Data acquired when the imager and sounder view space and the onboard blackbody determine the slope and intercept but not the coefficient of the quadratic term in the calibration equation. That coefficient is determined in thermal vacuum tests before launch by exposing the imager and sounder to a laboratory blackbody at temperatures between 180 and 320 K; the blackbody calibration is traceable to the National Institute of Standards and Technology. This calibration procedure is repeated several times with the imager and sounder held at different temperature "plateaus," whose range exceeds the operating temperatures expected in flight. Thus, the quadratic coefficient for the calibration of each spectral band is characterized as a function of instrument temperature.

Calibration slopes and intercepts are computed in the SPS computer at the Wallops CDA in real time. Slopes are recomputed immediately after the imager or sounder views its onboard blackbody. The temperature of the blackbody is determined as an average of the readings from the eight thermistors. The radiance of the blackbody is calculated from the convolution of the Planck function over the spectral response of the instrument.

## 4. WEFAX, DCP, SEM, and SAR services on GOES I-M

The WEFAX service has been a feature of the GOES system since 1975. The service uses the spacecraft as a transponder to transmit low-resolution imagery sectors as well as conventional weather maps to users with low-cost reception equipment. There are hundreds of WEFAX reception stations throughout the western hemisphere that use the GOES WEFAX service. With the GOES–VAS system, the WEFAX service was provided at UHF frequencies and was not continuous since it interfered with other spacecraft functions. The WEFAX service with GOES I-M is a continuation of the prior service; however, transmissions are continuous, and the transmission frequency has changed from UHF to S band, 1691.0 MHz, with a signal bandwidth of about 30 kb $s^{-1}$. Up to 13 maps or images can be transmitted through the GOES I-M every half hour, and it is the goal of the ground data handling system to transmit GOES I-M WEFAX imagery within a half-hour of its receipt.

DCPs, which relay environmental data through GOES satellites, have been an important part of the GOES system since its inception. The data collected at the DCPs provide a variety of observations, ranging from meteorological and oceanographic to remote hydrological and seismic station observations. Varying user requirements for each of those types of data led to a flexible GOES data collection system (DCS), which supports three basic types of DCP. They are (a) DCPs that relay data through the satellite at preprogrammed times, (b) DCPs that relay their data through the satellite when their sensors reach a predetermined threshold, and (c) DCPs that respond when interrogated through the GOES satellite. Currently, about 12 000 DCPs are assigned, serving about 300 users. The GOES I-M DCS, which can service up to 56 000 DCPs, has three major components. The primary component is the DCP, which may be placed at remote locations from which they relay environmental measurements through the second part of the system, the GOES I-M spacecraft. The data are transmitted from the DCP on one of 266-UHF (401 MHz) channels to the spacecraft where the signal is converted to S band and transmitted to the third component of the system, the Wallops Island CDA station. At the Wallops CDA, the data are sent to the DCS automated processing system (DAPS). At the DAPS, a variety of functions are performed that culminate in the environmental data being provided to the user community in several ways: (a) in real time through the commercial domestic satellite system, (b) by means of dedicated synchronous communication lines as output messages to NMC, and (c) through dial in modems using asynchronous communication lines.

With GOES I-M, the SEM subsystem continues to provide data to the joint NOAA and U.S. Air Force Space Environmental Services Center in Boulder, Colorado. The SEM is composed of four basic instruments that are based on proven designs that have evolved with improvements in component technology. The instruments are (a) a solar X-ray sensor, (b) a magnetometer, (c) an energetic particle sensor, and (d) a high-energy proton alpha detector. The instruments provide 24 h day$^{-1}$ measurements of ambient magnetic field vectors, solar X-ray flux, and multiple measurements characterizing the charged particle population for protons of energy greater than 0.8 MeV, alpha particles of energy greater than 3.2 MeV, and electrons greater than 0.6 MeV. The data are used in Boulder to monitor and predict solar activity and its effect on an array of activities. The activities include prediction of ionospheric conditions that affect radio transmissions, effects on electric power transmission grids, and radiation levels that affect high-altitude aircraft operations and manned space flight.

The GOES I-M system provides operational SAR support from geostationary altitude for the first time. This important complement to the polar-orbiting part of the SAR function allows nearly instantaneous detection of 406-MHz distress signals from special emergency transmitters that are carried on some aircraft and marine vessels. For detection, the distress signal must originate from within the GOES satellite's field of view; this means that regions beyond 75° from the satellite subpoint are not covered. The GOES I-M SAR does not position locate, as can be done using the polar system; however, it serves as an almost immediate alert to users that a distress signal has been broadcast. This allows search and rescue points of contact to expedite their investigations and rescue responses.

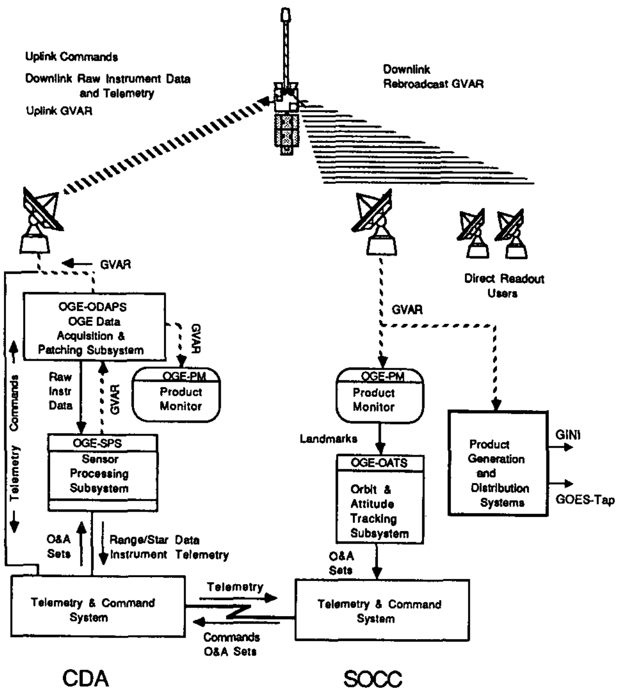

FIG. 3. Schematic data flow through the GOES I-M system. GOES-Tap and GINI will be broadcast by NESDIS from Washington, D.C.

## 5. GOES I-M data flow to the user and initial products

The GOES I-M spacecraft and the resultant flow of data to field users are supported by an extensive ground system (see Fig. 3). The Wallops Island CDA station supports the geostationary satellites. The Satellite Operations Control Center (SOCC), located in Suitland, continuously monitors the spacecraft and data acquisition systems and is responsible for spacecraft command scheduling. The CDA station provides the main point of communication with the GOES I-M satellites. The CDA houses those components closely associated with real-time acquisition of the raw data, production of the reformatted data stream, and retransmission of data through the spacecraft. The SOCC contains the remaining components associated with scheduling and planning, as well as off-line engineering and analysis functions; these are backed up by redundant copies at the CDA to ensure continued operation during communication outages or catastrophic failures of the SOCC.

For real-time weather forecasting, GOES I-M data must be transmitted nearly instantaneously to field users. A new ground data processing system enables efficient dissemination of data and products to users. This is accomplished using a completely redesigned GOES I-M Variable (GVAR) format for direct-receive users and existing GOES-Tap services for others. The GVAR format allows direct-receive users to acquire all data from the imager and sounder in real time. Transmission of GOES I-M images also occurs in either the GOES projection over the existing GOES-Tap system or remapped imagery by means of a new mode known as GOES-I NOAA-PORT Interface (GINI).

Archiving of the GOES data, started in 1978, will continue with the GOES I-M series. The GVAR data stream will be captured on the NESDIS videocassette archive housed at the University of Wisconsin—Madison. User access to the GOES archive is coordinated through the NESDIS Satellite Data Services Division (see section 9).

### a. *GVAR data stream for direct readout users*

The retransmitted GVAR stream provides users with calibrated data from the imager and both calibrated and raw data from the sounder, as well as the calibration and normalization coefficients in use with any set of data. The data stream also contains statistical summaries and quality indicators of the calibration process. Although the GVAR format is primarily used to transmit meteorological data provided by the imager and sounder, additional parameters associated with the measuring instruments are transmitted in the format, as are auxiliary products. The GVAR format has its origins in the operational VAS mode AAA format. The AAA format featured a fixed-length format composed of 12 equal-size blocks, with one complete 12-block sequence transmitted per rotation of the satellite. With the advent of the GOES I-M system, the range and flexibility of satellite operations are increased dramatically. The use of the variable length transmission format, GVAR, removes constraints that a fixed length would have placed on the satellite's capabilities, permitting full use of the new capabilities while maintaining as much commonality with AAA reception equipment as possible. GVAR maintains the 12-block sequence with imager documentation in block 0, imager data in blocks 1–10, and sounder data in block 11. GVAR is generated by the SPS, a portion of the operations ground equipment (OGE). Each SPS, one per spacecraft, generates a separate GVAR data stream. The SPS calibrates and normalizes imager and sounder data and generates grids and earth locations for imager data. Details concerning the GVAR format are given in McKenzie (1987).

Facilities with direct-receive capabilities such as NWS centers [NSSFC, the National Meteorological Center (NMC), and NHC] and the NOAA cooperative institutes CIMSS and CIRA (Cooperative Institute for Meteorological Satellite Studies and Cooperative Institute for Research in the Atmosphere) can receive OGE-calibrated and navigated data directly through the GVAR data stream. Because of the difference in sampling frequency and resolution of GOES I-M versus GOES–VAS (see Table 2), direct receive imagery from GOES I-M appears stretched in the east–west direction with respect to *GOES-7.*

Figures 4a,b illustrate the difference in aspect ratio for a *GOES-7* versus GOES-I visible image that will be noticed at direct-receive sites. The aspect ratio of the sampled subpoint resolution (E×W versus N×S) for *GOES-7* visible imagery is 0.87:1, while for GOES-I it is 0.57:1. When data are displayed as 1:1 picture elements, the result is a GOES-I image that appears stretched east–west with respect to a *GOES-7* image.

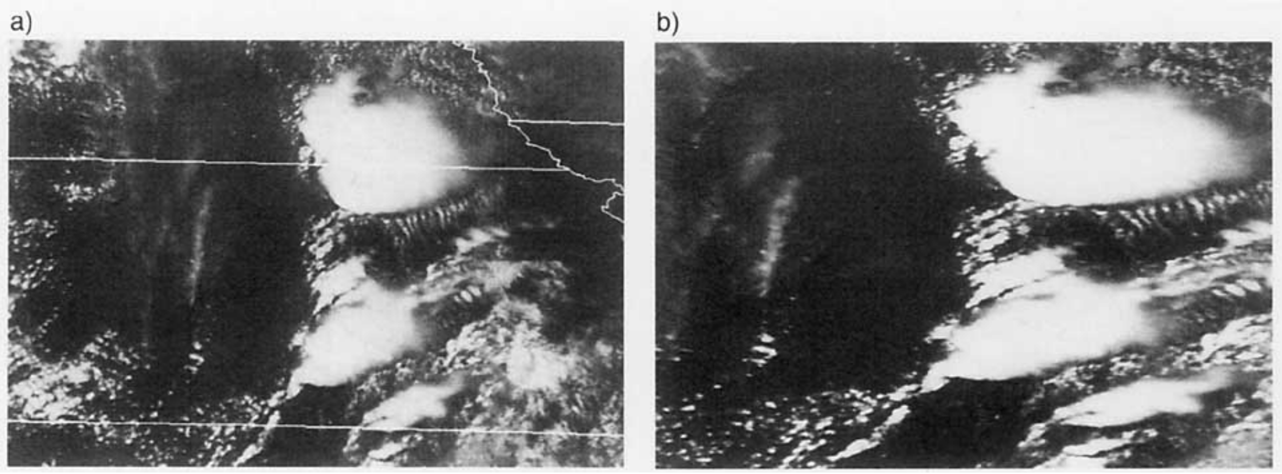

FIG. 4. (a) *GOES-7* and (b) simulated GOES-I visible images, from 1941 UTC 26 April 1992, illustrating the difference in aspect ratio.

### *b. Transmission of processed data to GOES-Tap and Advanced Weather Information Processing System (AWIPS) users*

At NESDIS, GOES I-M are produced in either full-disk, partial-disk, or sectorized format for transmission to users. There are two basic image formats: 1) the GOES projection for transmission over the existing GOES-Tap system (see section 9), and 2) remapped imagery in digital format to be made available to NOAA-PORT users by means of GINI [for more information see NOAA (1988)] and the NWS as a part of AWIPS. Although AWIPS will not be fully implemented at the beginning of the GOES I-M era, selected weather service offices will have facilities to evaluate the GINI products. The images transmitted through GINI and GOES-Tap are used for individual picture interpretation and for observing changes in weather systems with animated image sequences.

#### 1) GOES-TAP SYSTEM AND GOES-I IMAGERY

GOES-Tap images from GOES I-M are stretched in the east–west direction with respect to those currently produced from GOES–VAS. The sectors cover areas with equivalent resolutions of 1, 4, and 8 km. To maintain the same data format for transmission to existing facsimile equipment, the sectors are about 32% larger in area than those for GOES–VAS. This results in a slight reduction of the maximum resolution previously available from GOES–VAS. Although five image spectral bands are available from GOES I-M, only three are planned for day 1 transmission on the GOES-Tap system. Day 1 GOES-Tap transmission also includes one composite image (e.g., combined visible and infrared window image). The existing limitation of image frequency (30-min interval) still applies. Enhancement of the imagery is still provided, based on user requirements.

#### 2) AWIPS SYSTEM AND GOES I-M IMAGERY

Digital image sectors for the AWIPS system are produced at 8-bit depth for the continental United States (one eastern and one western) and for the Hawaii, Puerto Rico, and Alaska forecast areas. AWIPS imagery is remapped into a Lambert conformal projection for most sector types except for the Alaska sector, which is in the polar stereographic projection. All image bands plus three composite images are available at any time at full resolution. AWIPS sites can acquire full sectors for larger-scale applications, or smaller portions for regional (sectors 2000 or 1500 km on a side) or local (sectors 750 or 500 km on a side) scale applications. The frequency of the AWIPS images depends on the particular mode of operation (see section 5c).

Composite imagery for AWIPS will be multiband or multisatellite. In the AWIPS era, imagery from GOES-East and GOES-West are to be combined into one polar stereographic image covering much of the Northern Hemisphere. The images will be produced in three separate bands; visible, infrared window, and water vapor. Each image pixel will consist of an average brightness over an 8-km × 8-km area.

Two types of multiband composite images are planned: 1) a visible/infrared (VIS/IR), and 2) water vapor/infrared (WV/IR) combinations. The maximum resolution of each will be retained. VIS/IR images combine information from both types of imagery: the temperature structure of cold, precipitating cloud systems from the infrared and high-resolution depiction of mesoscale features such as low-level outflow and cloud line mergers from the visible. They also provide a smooth transition from daytime to nighttime monitoring of convection. VIS/IR images are already widely used by the NWS and are planned for day 1 distribution. The WV/IR composite is planned as a day 2 product. Important upper-air features such as jet streaks, troughs, and vorticity maxima are often well defined only in water vapor images.

### *c. Operational imaging modes and routine imager products*

#### 1) GOES-I IMAGER SCHEDULES

With the GOES-I imager, sector scanning is the standard mode of operation, as opposed to the GOES–VAS limb-to-limb partial-disk or full-disk scanning. This flexibility more than compensates for the fact that full-disk imaging is slower: 28 min for GOES-I versus 18 min for *GOES-7*. The GOES-I partial scanning makes almost any local sector area technically possible.

Initially, NOAA plans to support two basic modes of operation: routine and warning. In the routine mode, one full-disk image is taken every 3 h, and images covering the contiguous United States (CONUS) are taken every 15 min in the intervening times. The warning mode will be enacted when the onset of severe weather is imminent. In that mode, the CONUS is scanned eight times every hour for monitoring rapidly developing storms. Figures 5a,b show the anticipated coverage in the routine and warning modes of operation for GOES-I located at 90°W. NOAA will be initiating this new scheduling capability with GOES-I; however, it is subject to change pending satellite location decisions and a review of alternate scanning strategies.

#### 2) GOES-I IMAGER PRODUCTS

Beyond the raw and composite images, there are derived imager products that are modifications and improvements on those from *GOES-7*. They are

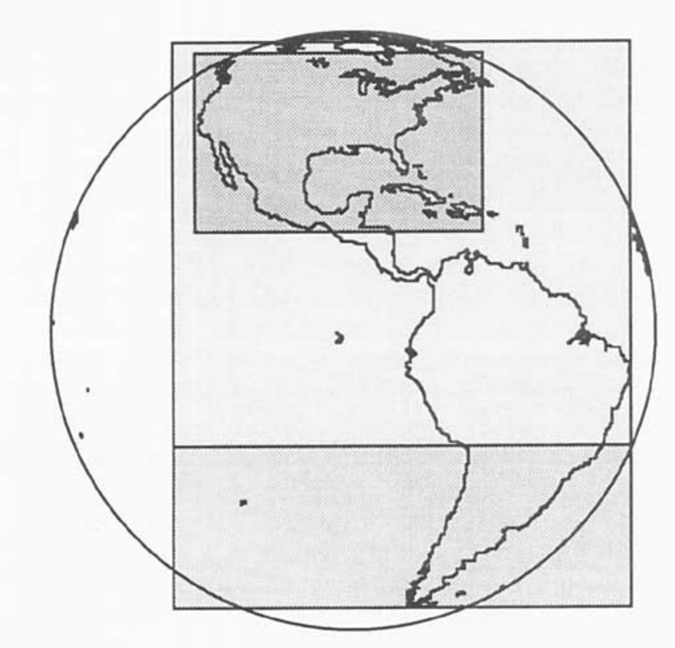

FIG. 5a. Coverage using the GOES-I imager in the routine mode. Extended Northern Hemisphere frame (covering down to 20°S) is followed by CONUS frame; remaining Southern Hemisphere frame concludes the half hour. Full-disk coverage occurs every 3 h.

FIG. 5b. Coverage using the GOES-I imager in the warning mode. Half-hour sequence proceeds as follows: Northern Hemisphere frame (covering down to the equator), CONUS frame, small Southern Hemisphere frame, CONUS frame, and CONUS frame. Small Southern Hemisphere frame could be defined for any one of several geographic areas.

cloud and moisture-drift wind fields, lifted indexes, total precipitable water vapor, and heavy precipitation estimates.

Cloud-drift wind fields are derived using a sequence of three half-hourly images. The winds are calculated by a three-step objective procedure. The initial step selects targets, the second step assigns pressure altitude, and the third step derives motion. Target selection involves searching for regions of maximum brightness and temperature gradients, with the horizontal density of the search controlled by an input parameter (usually about 150-km spacing). Initial cloud height assignments for the selected targets are made using the $H_2O$ intercept method that is currently used with Meteosat (Nieman et al. 1993). This is a departure from the GOES–VAS approach, where height assignments are made using the $CO_2$ slicing technique (Menzel et al. 1983); although the latter has been shown to be the preferred approach, there is no $CO_2$ 13.3-$\mu$m band on the GOES-I imager, and $H_2O$ intercept heights are of comparable quality (Nieman et al. 1993). Both height algorithms involve multispectral radiative transfer calculations in the environment of the target that account for the differing radiative attenuation as a function of cloud height. An initial-guess motion, based on NMC wind forecasts at the estimated cloud level, is used to steer the pattern recognition algorithm that locates the "target area" in one image within a "search area" in the second image and again in the third image using cross-correlation techniques. The first-guess motion, the consistency of the two winds, the precision of the cloud height assignment, and the pattern recognition feedback are all used to assign a quality flag to the "vector" (which is actually the average of two vectors). The initial height assignments are quality controlled, and some are adjusted through comparison with ancillary data (e.g., the 6-h model forecast and aircraft wind reports). Winds from moisture imagery (6.7 $\mu$m) are derived by the same methods used with cloud-drift imagery; heights are assigned from the water vapor brightness temperature. Winds derived using cloud-drift and moisture-drift techniques are complementary in areal coverage. Cloud-drift winds are produced primarily in cloudy and partly cloudy areas, while moisture-drift winds are generated in mostly clear areas. The improved signal in the GOES-I water vapor images is expected to enhance the quality and utility of the moisture-drift winds appreciably. Satellite cloud-drift winds are input into NMC numerical models and are transmitted worldwide on the Global Telecommunications System (GTS).

Total precipitable water vapor (PW) and lifted indices (LI) are produced as derived product images, using the longwave split windows, the shortwave window (at night), and the 6.7-$\mu$m water vapor bands.

Derived product imagery is formed from pixel-by-pixel retrievals of atmospheric temperature and moisture profiles wherever the atmosphere is quasi-clear. The images appear as the derived product with the cloud cover superimposed (see Hayden and Schmit 1991). Examples of the PW product are shown in Fig. 10a,b. These products are made available hourly by NESDIS for use by the NWS national centers. Precipitable water vapor and LI are discussed in more detail in section 5d, which addresses sounder products.

GOES imagery is also used to produce precipitation estimates for heavy rainfall events. These estimates are made at the NMC in Washington, D.C., using an interactive flash flood analysis (IFFA) system. The IFFA estimates are based on a modification of the Scofield–Oliver technique (Scofield 1987) and depend on a number of factors such as infrared temperature, cold cloud area growth rate, cloud shield pattern, merging cloud tops, and overshooting tops. The 6.7-$\mu$m water vapor imagery is used to detect tropical water vapor plumes that are often associated with extreme rainfall events (Thiao 1993). The GOES-I version of this technique takes advantage of the higher spatial and temporal resolution multispectral imagery.

### *d. Operational sounding modes and routine sounder products*

#### 1) GOES-I SOUNDER SCHEDULES

The GOES-I sounder primarily covers the contiguous United States and adjacent ocean areas every hour, from which cloud products in support of ASOS and atmospheric temperature and moisture soundings for input to numerical forecast models will be generated. During periods of severe weather and/or tropical cyclone activity, interruptions for 15-min mesoscale/tropical coverage may occur. As with the imager, two basic modes of operation—routine and warning—have been suggested. As this article goes to press, adjustments to the sounder schedules are still under consideration; after the launch of GOES-J, more frequent sounder coverage of the oceans will be scheduled.

In the routine mode, starting at 0000 UTC, NOAA schedules 1-h regional scans (50°–25°N and 70°–120°W) for the first 5 h. During the winter season (December–May), the sixth hour is dedicated to a Southern Hemisphere 1-h regional scan for the generation of soundings for input to forecast models. During the summer season (June–November), the sixth hour has a 45-min limited regional scan over the CONUS (45°–30°N and roughly 70°–120°W), followed by a 15-min mesoscale scan (15° latitude by 15° longitude) over the location of a tropical disturbance. This 6-h schedule is repeated four times each 24 h.

The warning mode is enacted when the onset of severe weather is imminent; the location of the mesoscale coverage is adjusted as the weather situation dictates. In the warning mode, 15-min mesoscale scans are scheduled four times an hour over the area of severe weather for the first 2 h. During the third hour, one 15-min mesoscale scan is followed by a 45-min limited regional scan over the CONUS. This 3-h schedule is repeated as long as the warning mode persists.

#### 2) GOES-I SOUNDER PRODUCTS

NOAA begins operational geostationary sounding for the first time with GOES-I. Several GOES-I sounder products are planned initially; they include the clear field of view (FOV) brightness temperatures and profile retrievals of temperature and moisture, as well as the temperature and moisture layer mean values, lifted indices, and thermal wind profiles.

Vertical temperature profiles from sounder radiance measurements are to be produced at 40 pressure levels from 1000 to 0.1 mb using a physical retrieval algorithm (Hayden 1988) that solves for surface skin temperature, atmospheric temperature, and atmospheric moisture simultaneously. Also, estimates of surface emissivity, cloud-top pressure, and cloud amount are obtained as by-products. The retrieval begins with a first-guess temperature profile that is obtained from a space–time interpolation of fields provided by NWS forecast models. Hourly surface observations and sea surface temperature from AVHRR help provide surface boundary information. Soundings are produced from a 5 × 5 array of FOVs whenever nine or more FOVs are determined to be either clear or contaminated by "low cloud."

Vertical moisture (mixing ratio—hence, specific humidity) profiles are obtained in the simultaneous retrieval and are provided at the same levels as temperature up to 300 mb. Since the radiance measurements respond to the total integrated moisture above a particular pressure level, the specific humidity is a differentiated quantity rather than an absolute retrieval. Layer means of either temperature or moisture can also be derived. Layered precipitable water can be integrated from retrievals of specific humidity; three layers (1000–900 mb, 900–700 mb, and 700–300 mb) and the total atmospheric column precipitable water are provided as output products and are put into the standard archive.

Lifted index, an estimate of atmospheric stability, is derived for each retrieval. It represents the buoyancy that an air parcel would experience if mechanically lifted from a mixed boundary layer to the 500-mb level. The lifted index expresses the difference in temperature between the ambient 500-mb temperature and the temperature of the lifted boundary-layer parcel.

Negative values (parcels warmer than the environment) represent positive buoyancy, with large negative values indicating the potential for severe storms; positive values denote stability. The formulation used to derive the lifted index is a thermodynamic relationship requiring the 500-mb temperature as well as a mean pressure, temperature, and moisture for the boundary layer. These quantities are all available from the retrieved profile.

Geopotential height profiles are derived from the full-resolution temperature and moisture profiles. The geopotential height of a pressure level is derived from a 1000-mb height analysis (from the NMC forecast supplemented with hourly data), a topography obtained from a library (with 10-min latitude–longitude resolution), and the retrieved temperature and moisture profile. Thickness can be calculated from this profile.

Thermal gradient winds, derived indirectly from the soundings, are provided with each profile. These are derived from objective analyses of the geopotential profiles calculated with each retrieval. The analyses are performed on a 1° latitude–longitude grid. Gradient winds are calculated using finite-difference operators that involve surface fitting over 5 × 5 grid points centered at the grid point closest to each retrieval. Wind estimates are provided from 700 to 400 mb. Verification studies with observed winds have shown that this product from VAS consistently depicts the temperature gradient more accurately than the 12-h NMC forecast. The GOES-I product should be an improvement and will have expanded geographical coverage. Cloud-drift and moisture-drift winds from the imager combined with thermal gradient winds from the sounder have been found to be of value in models for determining hurricane trajectories (Velden et al. 1992). These deep layer mean wind fields are produced with a pressure weighting of the winds at all levels.

The GOES-I sounder is also providing an hourly cloud product to supplement the ASOS. This is required by the NWS introduction of the ASOS nationwide. ASOS is designed to support weather forecast activities and aviation operations. ASOS uses automated equipment to provide near-continuous observations of surface weather data including cloud height and amount that are currently obtained by NWS and Federal Aviation Administration observers. The cloud information from the ASOS equipment is limited to altitudes below 12 000 ft, and GOES-I provides supplemental information about cloud cover above 12 000 ft at each ASOS site. The combined ASOS/satellite (ASOS/SAT) system depicts cloud conditions at all levels to 25 000 ft. Because observations are required every hour, the satellite cloud product can be derived only from the geostationary spacecraft data. The satellite cloud information is derived using sounder data with the $CO_2$ slicing technique, which calculates both cloud-top pressure and effective cloud amount from radiative transfer principles. It also reliably separates transmissive clouds that are partially transparent to terrestrial radiation from opaque clouds in the statistics of cloud cover. For a given ground observation site, the algorithm uses radiation measurements from an area of roughly50 km × 50 km centered on the site. Further information can be found in Schreiner et al. (1993).

## 6. Simulations of GOES-I images and soundings

To help assess the potential impact of imagery and products from the GOES-I system, simulations were performed at two NOAA cooperative institutes. Image simulations were carried out at CIRA, which is located at Colorado State University. Derived product image and sounding simulations were undertaken at CIMSS, which is located at the University of Wisconsin.

### *a. GOES-I imager simulations*

The GOES-I imagery was simulated from 10-bit NOAA AVHRR data. Those simulations show that GOES-I imagery should be a significant improvement over data routinely available from the current GOES–VAS system. The major reasons are the greater dynamic range afforded by 10-bit versus 6-bit visible imagery and the improved spatial resolution in all of the infrared bands. The simulations used *NOAA-11* and *NOAA-12* AVHRR visible, 3.7-, 10.7-, and 12.0-$\mu$m infrared imagery. The specified GOES-I infrared response function and IGFOV were imposed on the AVHRR imagery in a manner similar to that discussed by Gabriel and Purdom (1990). Field-of-view size was expanded according to latitude–longitude distance from the subpoint. Gaussian white noise was added to the AVHRR 10-bit visible image to simulate that expected with GOES-I. There is no 6.7-$\mu$m band on AVHRR, and simulations were not made for that band; however, indications are that it will provide an improved image product due to the reduction in noise and better resolution at 6.7 $\mu$m (see section 6b for sounder simulations of the water vapor band).

In the simulated imagery presented here, AVHRR and *GOES-7* imagery were taken within a few minutes of each other and mapped to *GOES-7* projection for direct comparison. The AVHRR data were assumed to be noise-free and were treated as though they were 1-km × 1-km resolution at all pixel locations (only true at the subpoint); these assumptions should lead to a simulated image that is inferior to an actual GOES-I image.

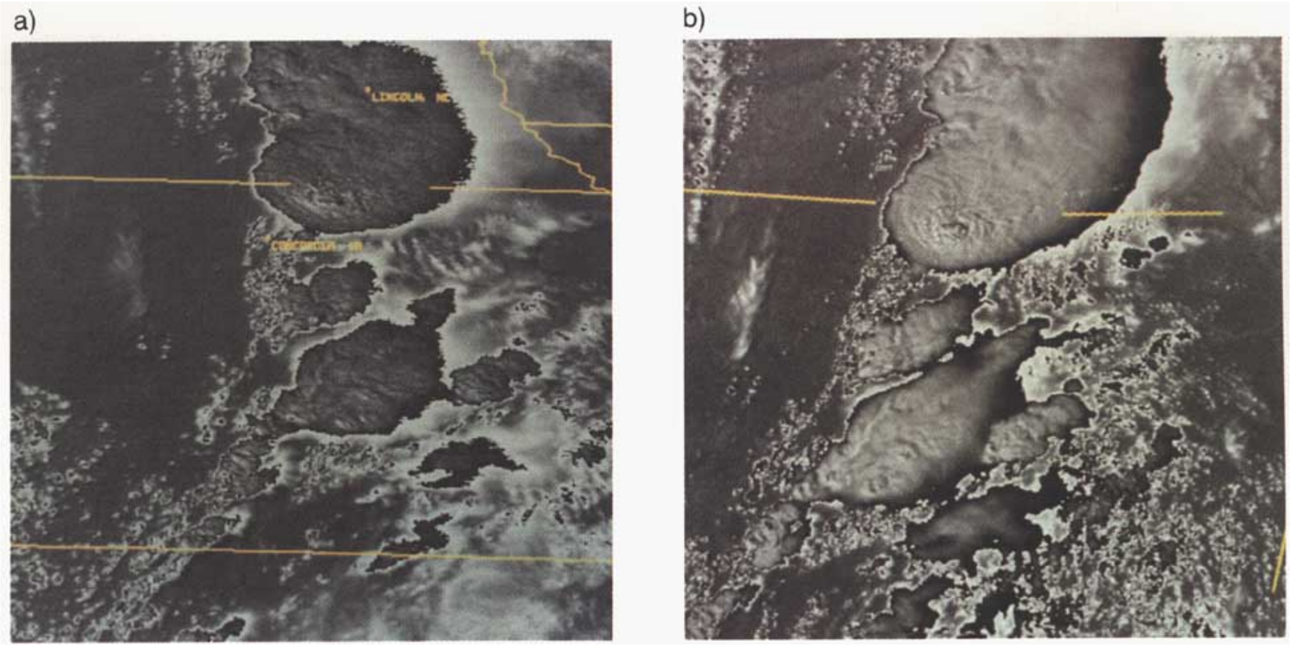

FIG. 6. *GOES-7* 6-bit and simulated GOES-I 10-bit visible images from near 2011 UTC on 26 April 1992, illustrating the expected improvement in detection of cloud-top features using higher bit depth visible imagery. The *GOES-7* image (a) and simulated GOES-I image (b) have been enhanced to show detail at cloud top.

Figures 6a,b illustrate the expected improvement in detection of cloud-top features using 10-bit GOES-I visible imagery. Notice the detail in the overshooting top area and other regions of the anvil in the simulated GOES-I image. The storm with the well-defined overshooting top just south of the Kansas–Nebraska border (–67°C in Fig. 7b) was a supercell that produced hail, damaging winds, and a series of F2 and F3 tornadoes.

Figures 7a,b are infrared images from the same time as Figs. 6a,b and show the same thunderstorm

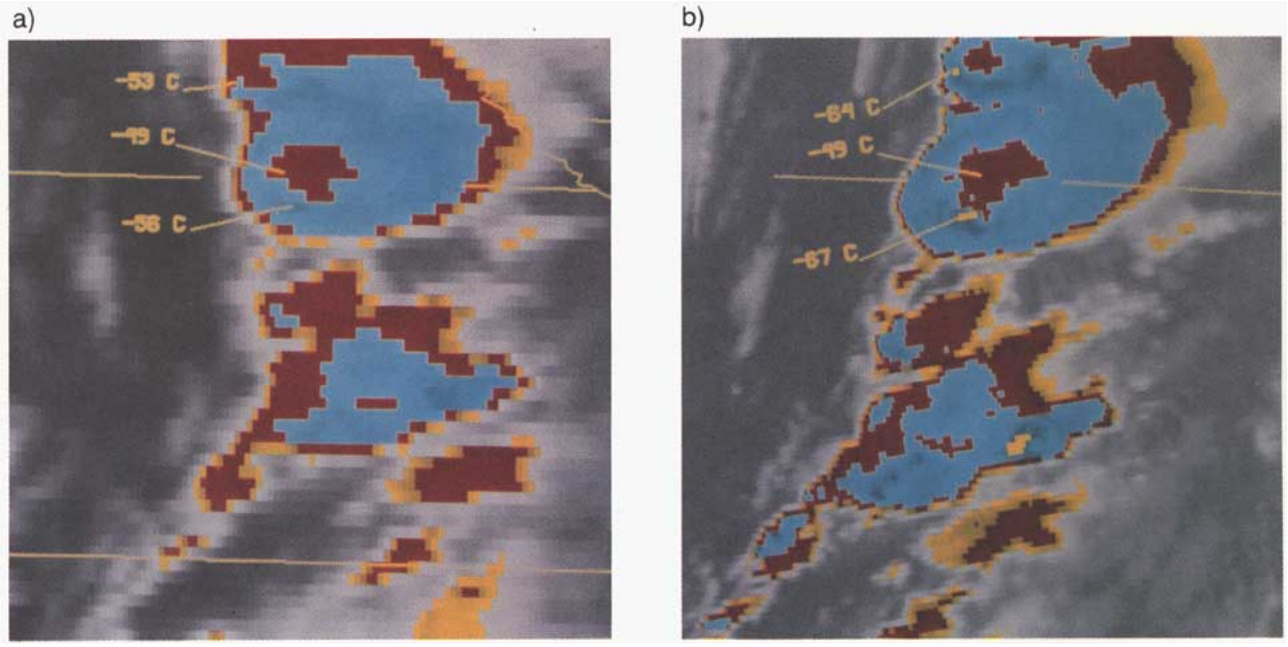

FIG. 7. *GOES-7* and simulated GOES-I infrared window images of the same thunderstorm top at the same time as Fig. 6. The *GOES-7* image (a) and simulated GOES-I image (b) have been color enhanced to show detail at cloud top. Brightness temperatures are superimposed.

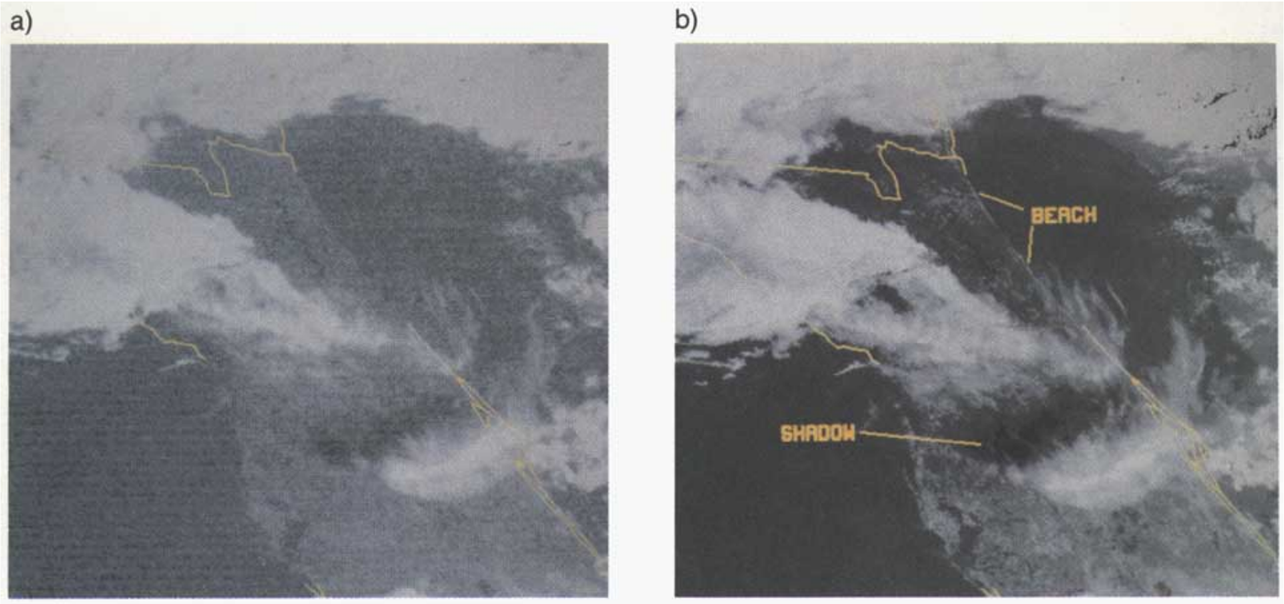

FIG. 8. *GOES-7* and simulated GOES-I visible images over Florida shortly after sunrise on 21 December 1992. The AVHRR image from which the GOES-I image was simulated (b) was taken about 15 min earlier than the *GOES-7* image (a).

area. The figures illustrate the expected improvement in detection of cloud-top features due to the improved resolution of GOES-I at 10.7 $\mu$m. Cold overshooting top areas are easily detected in the simulated GOES-I imagery. The storm along the border, discussed above, has a well-defined cold top and downstream warm wake that are easily detected in the simulated GOES-I imagery. Such features have been associated with severe thunderstorms (Heymsfield et al. 1988). The coldest cloud-top temperature was measured at −74°C in the original AVHRR image; GOES-I shows −67°C, while *GOES-7* shows only −56°C. It is interesting that the cold top (−64°C in Fig. 7b) in Nebraska has a similar anvil structure that is readily detected in the simulated GOES-I image but not in the *GOES-7* image. That storm produced large hail and an F1 tornado.

Figures 8a,b were taken shortly after sunrise on 21 December 1992; comparison of the images illustrates

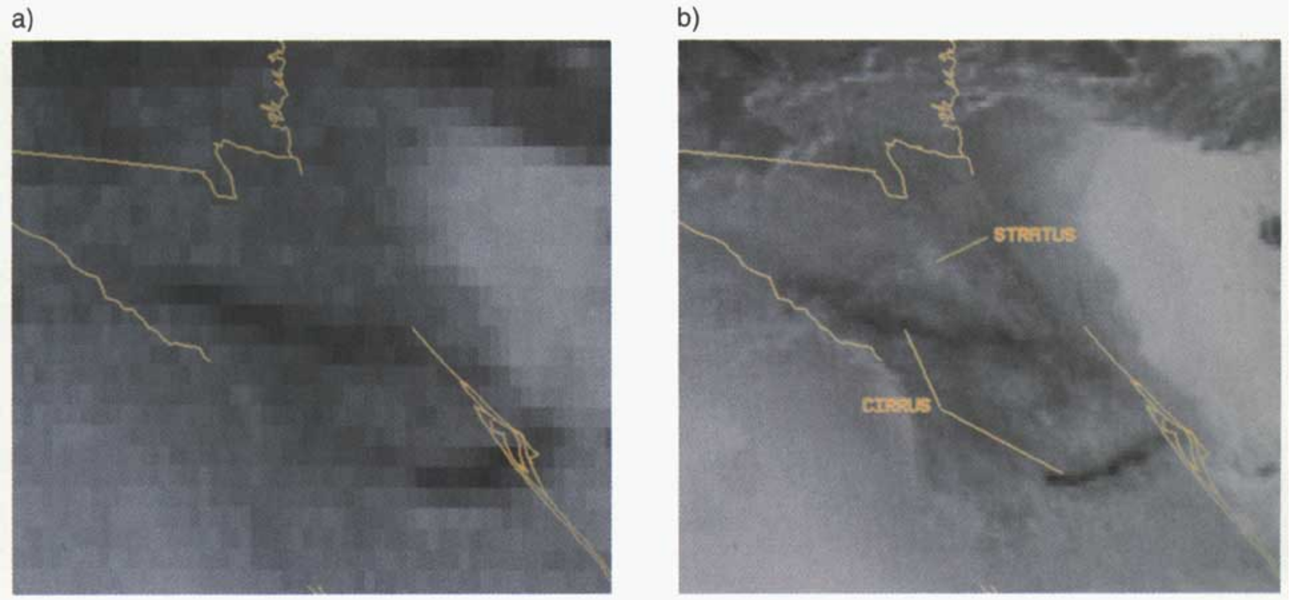

FIG. 9. The 3.9-$\mu$m images for the same times as Fig. 8 comparing *GOES-7* imagery (a) with simulated GOES-I imagery (b). These images are displayed as reflectivity.

the ability to detect low-light features in GOES-I imagery. The *GOES-7* and simulated GOES-I images are enhanced to show maximum detail in dark regions. Notice how well the light sand beaches, cloud detail, and shadows show up in the simulated GOES-I image. Cloud shadows enable computation of very accurate cloud heights, which promise to be valuable ancillary information for cloud-drift winds and ASOS cloud products.

Figures 9a,b are 3.9-$\mu$m images for the same times as Figs. 8a,b, and compare *GOES-7* imagery with simulated GOES-I imagery. Since 3.9-$\mu$m imagery has both reflected and emitted radiation, a choice must be made on how to display that imagery. Usually, 10.7-$\mu$m imagery is displayed with warm scene temperatures (large brightness temperature) as dark tones and cold scene temperatures (low brightness temperature) as bright tones; the reverse is true for visible imagery where bright surfaces such as clouds are displayed as bright tones and dark features are dark tones. These 3.9-$\mu$m images are displayed as reflectivity: at 3.9 $\mu$m, cirrus (large particle ice clouds) are poorly reflective and cold (very dark tones), while low clouds with small water droplets are bright and relatively warm (lighter tones). Comparison of Figs. 8b and 9b allows discrimination between low and high clouds, and perhaps cloud phase. When the 10.7-$\mu$m band is used to add cloud-top temperature information, the potential exists to isolate regions of supercooled cloud.

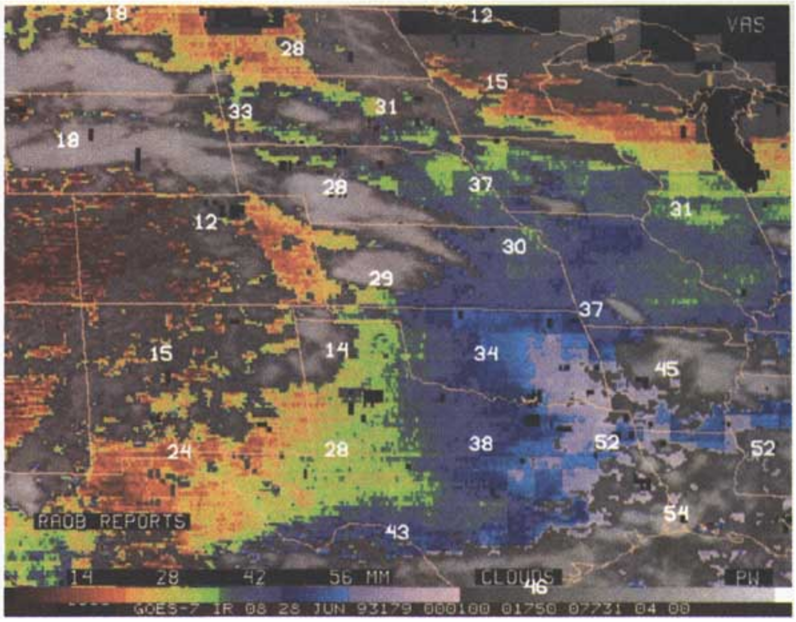

FIG. 10a. *GOES-7* derived product image on 28 June 1993 at 0000 UTC of total precipitable water using the longwave split window and the water vapor bands; radiosonde reports are superimposed to provide a comparison.

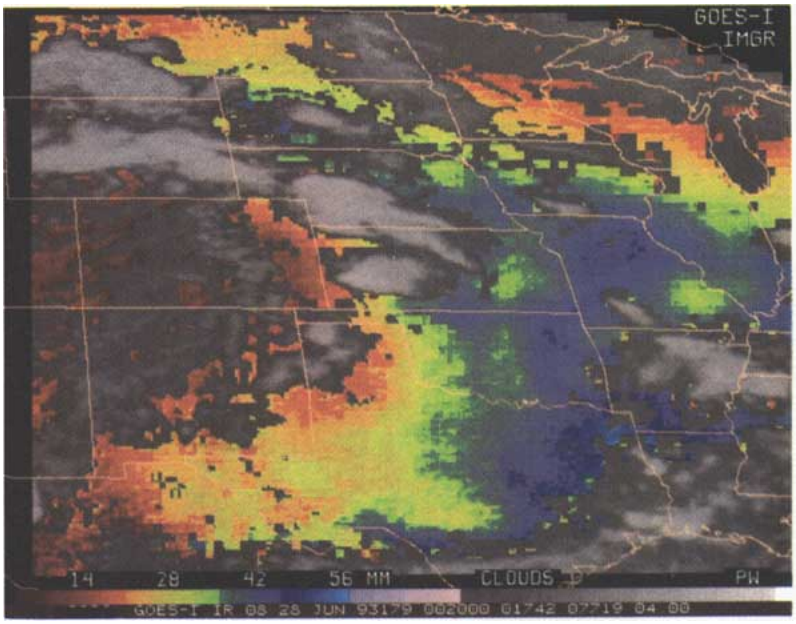

FIG. 10b. Simulated GOES-I derived product image on 28 June 1993 at 0020 UTC of total precipitable water using the longwave split window and the water vapor bands.

Figure 10a shows a GOES–VAS (*GOES-7*) derived product image on 28 June 1993 at 0000 UTC of total PW calculated using radiance measurements from the longwave split window and the water vapor bands. Radiosonde reports are superimposed, and general agreement in synoptic trends is evident. Figure 10b shows the simulated GOES-I imager derived product image for 28 June 1993 at 0020 UTC of PW using the comparable imager spectral bands. The GOES-I PW image is cleaner and depicts moisture gradients (e.g., across Texas) on smaller scales than *GOES-7*; this is a direct result of GOES-I improvements in spatial resolution and signal to noise.

### *b. GOES-I sounder simulations*

GOES-I soundings were simulated using VAS, radiosonde, and weather forecast model data over a

FIG. 11. *GOES-7* visible imagery for 0000 UTC 22 July 1993.

limited domain (approximately 25° latitude by 30° longitude). The "true" atmosphere was defined by an analysis from a CIMSS local regional assimilation system, VAS retrievals, and rawinsonde reports. GOES-I measurements were simulated by a forward radiative transfer calculation using that "truth." VAS observations were used to obtain cloud information and skin temperature estimates, and random error was added to simulate anticipated measurement noise. GOES-I temperature and moisture retrievals were made with a simultaneous physical retrieval (Hayden 1988) using an NMC regional model 12-h forecast as a first guess (to provide some independence from the truth). Finally, the simulated GOES-I retrievals and the collocated NMC forecast profiles were compared to the truth.

Principal conclusions are that the GOES-I sounder provides significant improvements in both coverage and accuracy compared to the current VAS product. Furthermore, results show that the data should be beneficial to the numerical forecast products, especially with regard to moisture. This conclusion is based on statistics that show that the retrievals are generally more accurate than the 12-h forecast (whereas current VAS is slightly worse in temperature and modestly better in moisture). Naturally, caveats apply. These results are based on simulation both in terms of what is believed to be the true state of the atmosphere and realistic radiance measurements. Neither is perfect, and history attests that a simulation of this type is almost always optimistic. To prepare for operational use of GOES-I sounder data, NMC and NESDIS are planning to conduct joint tests with simulated GOES-I moisture soundings in the NMC Eta model.

Figure 11 shows the *GOES-7* visible image for the retrieval domain at 0000 UTC on 22 July 1993. The weather situation is typical of a summer afternoon. Figure 12a shows the VAS and Fig. 12b shows the GOES-I sounding coverage, the former plotted over the observed infrared window and the latter over the simulated infrared window. The retrieved lifted index is indicated at the location of each sounding. The VAS is processed at an 11 × 11 FOV density and the GOES-I at a more dense 5 × 5 FOV. Retrievals are attempted when 25 and 9 FOV are estimated to be cloud-free for the VAS and GOES-I, respectively. The improved coverage and the ability of the GOES-I to find holes in the vicinity of clouds is obvious.

Figure 13a presents the VAS 6.7-$\mu$m measurements (the water vapor band) as obtained in sounding

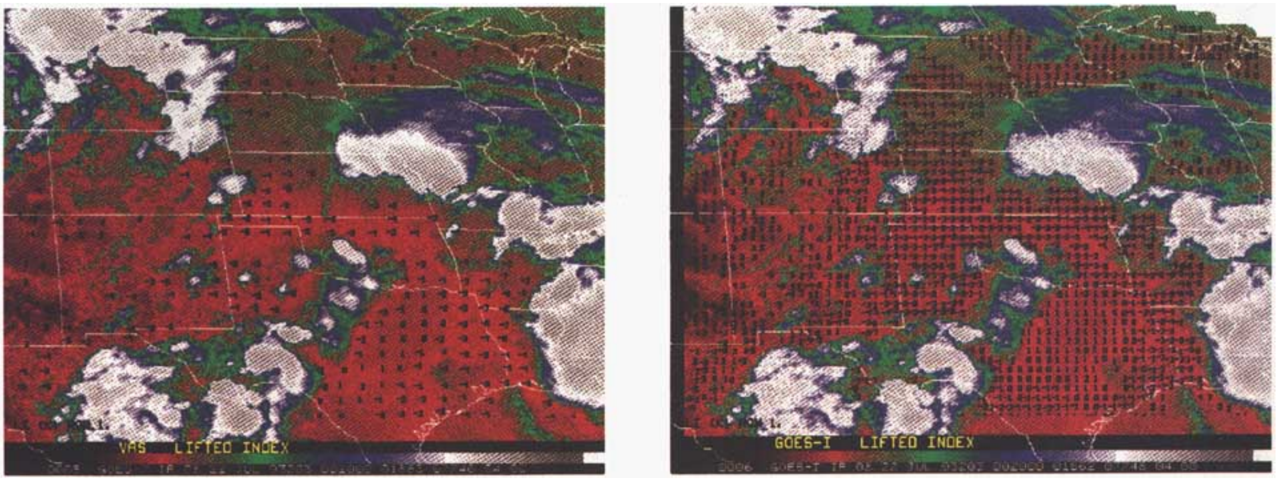

FIG. 12. (a) *GOES-7* infrared window image and retrieved lifted indexes for 0000 UTC 22 July 1993. (b) GOES-I simulated infrared window image and sounder retrieved lifted indexes for 0000 UTC 22 July 1993.

(as opposed to imaging) mode. The striping is caused by skipping every other pair of lines in order to increase latitude coverage for soundings in a given time period (necessary because the GOES–VAS imaging and sounding functions are time shared). The cloud clearing suffers accordingly. Figure 13b presents a similar (slightly lower in the atmosphere) band simulated for GOES-I. The moisture patterns are very similar, though better defined with GOES-I, which has a better signal-to-noise definition. The cloud contamination simulated at this wavelength appears to be reasonable. It should be noted that clouds are simulated at only one level, certainly not realistic but adequate for the purpose of defining fields of view that are not clear, and that is the criterion for rejection in the current retrieval algorithm (i.e., no partly cloudy FOVs are considered).

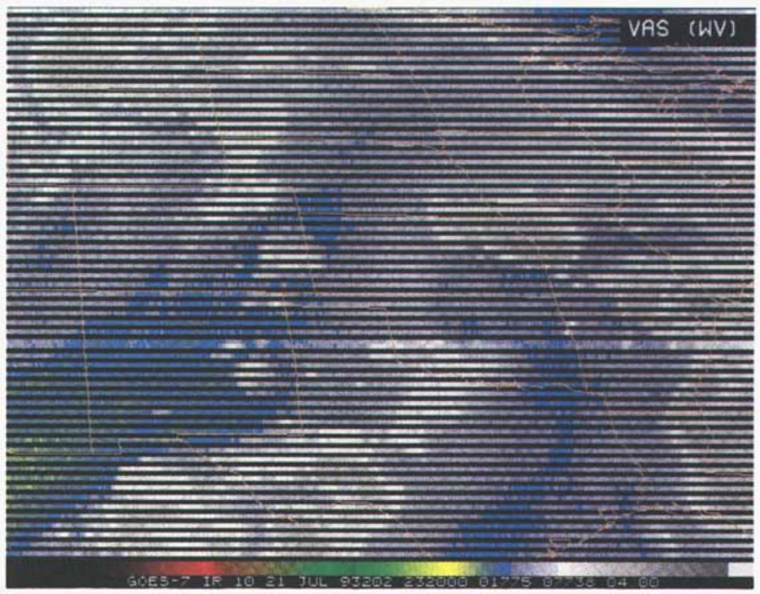

FIG. 13a. *GOES-7* 6.7-$\mu$m measurements for 2320 UTC 21 July 1993. Banding is caused by the skip-step mode of operation.

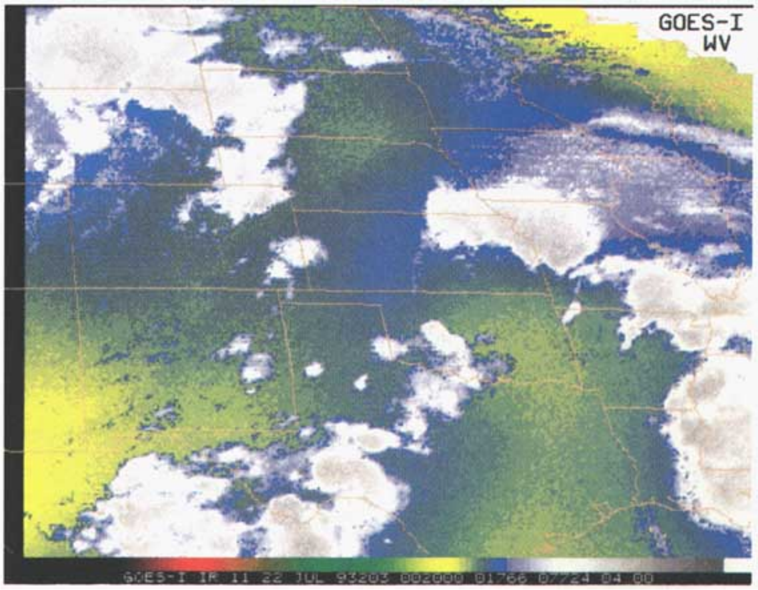

FIG. 13b. GOES-I simulated 7.0-$\mu$m measurements for 0020 UTC 22 July 1993.

The rms statistics of the retrieved temperature and moisture profiles with respect to radiosondes show that the temperature and dewpoint at several levels of the atmosphere for the GOES-I retrievals improve upon the 12-h NMC forecast by 0.5°–1.0°C. This is especially apparent for moisture. At some levels, temperature accuracy is within 1.5°C, but one should not lose sight of the fact that these excellent numbers are obtained chiefly because the forecast first guess is already excellent. Since the forecasts will likely continue to improve in both accuracy and resolution, so too must the sounders if they are to remain useful. An appropriate conclusion from these comparisons is that the GOES-I sounder and processing system is much better than VAS and should be of great benefit to numerical weather prediction responsibilities of the next decade. However, with the thrust of the NWS modernization directed toward improved accuracy of forecasts (local, mesoscale, synoptic scale, and long range), future improvements in the sounder beyond that of GOES I-M will be required.

## 7. Future products

The high-resolution multispectral nature of GOES I-M imagery will lead to a variety of advanced products through the development of algorithms that combine and compare the various spectral bands. Signal to noise for the 3.9-$\mu$m band approaches that at 10.7 $\mu$m at warm temperatures; this should foster the development of a number of improved products for analyzing earth surface characteristics and cloud-top properties. On GOES I-M, the 12.0-$\mu$m band covers a broader spectral width than GOES–VAS; the resulting signal-to-noise improvement should lead to the development of improved low-level moisture and sea surface tem-

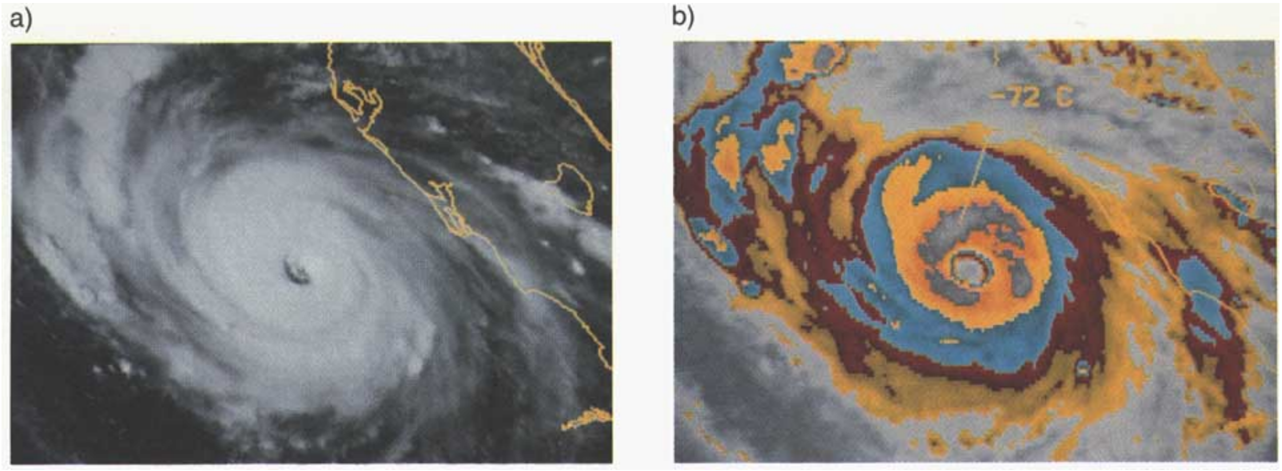

FIG. 14. Simulated GOES-I visible and infrared window images of Hurricane Andrew on the afternoon of 24 August 1992. The visible image is displayed in (a) and the corresponding 10.7-$\mu$m infrared image is displayed in (b) using a color enhancement table.

perature (SST) products during daytime. At night, an improved SST should be realized by adding information from 3.9 $\mu$m because of less diffraction at that wavelength. Also, because differences in phase, droplet size, and droplet distribution lead to different radiative properties [e.g., albedo, diffuse transmission, radiative flux divergence (heating rates), radiance] of clouds at the different wavelengths, a number of advanced products for areas as diverse as nowcasting and climate change should be possible. The potential for an advanced image product portraying cloud reflectivity as well as emissivity at 3.9 $\mu$m is shown in Fig. 14d, which should be compared to Figs. 14a–c.

The GOES I-M imager offers exciting possibilities for the development and implementation of improved precipitation products. The present IFFA will benefit from the improved infrared resolution of the GOES I-M. The convective stratiform technique (Adler and Negri 1988), an automated precipitation estimation program, will be used to monitor all convective systems over the United States and to provide hourly rainfall estimates for mesoscale models.

The GOES I-M imager will be able to monitor trends in biomass burning; recent work has demonstrated the advantage of using the constant surveillance of GOES to sense fires as they burn (Prins and Menzel 1992). The diurnal nature of the burning often causes polar-orbiting estimates to be in error. Using the longwave and shortwave infrared window radiance measurements of burning regions, the areal extent and temperature of the fires can be estimated. The GOES-I improved spatial resolution and enhanced signal to

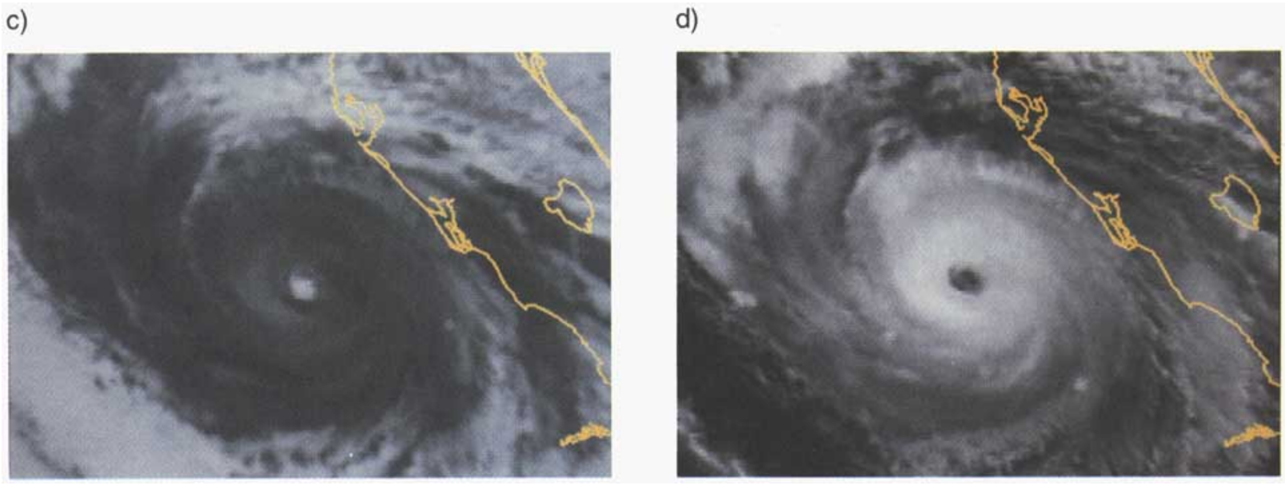

FIG. 14. Simulated GOES-I 3.9-$\mu$m imagery (c) (displayed as reflectivity) and a simulated GOES-I image product (d) made by subtracting the brightness temperature at 10.7 $\mu$m from that at 3.9 $\mu$m. The difference image (displayed as reflectivity) shows reflected radiation at 3.9 $\mu$m plus the difference due to emissivity times the Planck function at the respective wavelength intervals.

noise in the infrared bands will improve this capability already demonstrated with the GOES–VAS.

The GOES I-M sounder has the capability to depict boundary-layer properties that may be influencing the development of convective activity. The shortwave bands will provide improved surface skin temperature and lower-layer moisture determinations. The net flux divergence and the inferred cooling rate will be determined on the mesoscale; these can be used to describe the radiative processes over terrain inhomogeneities surrounding atmospheric instabilities.

The ozone band on the sounder offers the opportunity to monitor total atmospheric ozone seasonal trends as well as diurnal fluctuations. The 9.7-$\mu$m band can be combined with the stratospheric bands of the sounder to estimate total integrated ozone (Ma et al. 1984). The carbon dioxide bands on the sounder will allow continuation of an 8-year study of the fluctuations in diurnal and seasonal cirrus cloud cover over North America (Menzel et al. 1992).

## 8. Conclusions

Since all components of the GOES-I system come from new designs, the spacecraft will undergo an extensive 6-month checkout before data begins flowing to users on a routine operational basis. During this checkout phase, GOES-I will be located near 90°W; *GOES-7* at 112°W, providing eastern Pacific coverage; and *Meteosat-3* at 75°W, providing Atlantic basin coverage (de Waard et al. 1992). This maximizes overlap between GOES-I and *GOES-7* for intercomparison while centering GOES-I over the continental United States network of ground-truth observations. Final positioning of GOES-I, *GOES-7,* and *Meteosat-3* will be determined during the 6-month postlaunch system checkout. The launch of GOES-J is scheduled to take place one year after the launch of GOES-I, and following its checkout period, NOAA's geostationary satellite fleet will be completely modernized and, it is hoped, will operate with an expanded three-satellite capability.

In this article, simulated GOES-I imagery has been presented for comparison with imagery from the current *GOES-7.* Those simulations show that GOES-I should represent a notable advance in geostationary satellite imaging capability and will provide another powerful tool for analysis of the earth's atmosphere. Expected improvements and anticipated advances using each spectral band are summarized in the following.

1) At 0.52–0.72 $\mu$m (visible), major improvements are in 10-bit versus 6-bit imagery and increased sampling frequency. The increased sampling frequency should allow for better cloud-edge detection, while the 10-bit versus 6-bit improvement will provide 1024 versus 64 brightness levels. With proper image enhancement, those new capabilities should allow for (a) improved cloud-edge and cloud-top feature detection, which should lead to improvements in cloud-drift winds and severe storm identification; (b) extended use of visible imagery into low-light situations; (c) detection and potential assessment of pollution and haze; and (d) highly accurate cloud height measurements during daylight hours using both stereo and cloud shadow techniques.
2) At 3.78–4.03 $\mu$m (shortwave infrared window), major improvements in resolution (2 km × 4 km versus 4 km × 16 km) and sensitivity (0.15 K versus 0.25 K at 300 K) will greatly increase our ability to identify fog at night, locate water clouds over snow during the daytime, delineate between supercooled and ice cloud during daytime (with longwave IR), and detect hot areas such as fires and volcanoes. The improved resolution should also aid in hurricane eye location when the eye is covered with thin cirrus. At night, this band has the potential of improving sea surface temperature measurements due to decreased diffraction effects (versus longwave IR bands).
3) At 6.47–7.02 $\mu$m (water vapor band), there is a twofold improvement in spatial resolution and a factor of 3 improvement in signal to noise. Those improvements will be obvious in the routine loops of water vapor imagery used to estimate regions of midlevel moisture advection and drying. Additionally, GOES-I should yield better winds in cloud-free areas and improved identification of synoptic-scale features.
4) At 10.2–11.2 $\mu$m (longwave infrared window), a near fourfold improvement in spatial resolution should lead to improvements in cloud-edge and cloud-top feature detection. This should allow for improvements in cloud-drift winds, severe storm identification, and location of storms with heavy rainfall. In combination with the 11.5–12.5-$\mu$m band improvements, better low-level moisture identification should result. With the 11.5–12.5- and 3.78–4.03-$\mu$m bands, improvements in nighttime SST determination should be realizable.
5) At 11.5–12.5 $\mu$m (split window), there is an eightfold increase in resolution over what is available today. Furthermore, this band covers a larger spectral width than with GOES–VAS, and its resulting signal-to-noise improvement (equivalent to the 10.2–11.2-$\mu$m band) should lead to the development of much more accurate low-level moisture and improved sea surface temperature products.

Improved low-level moisture products are valuable for all types of convective forecasting and in other situations where diabatic heating is important. In stable situations, this information has value for use in recognizing areas with a potential for radiation fog development.

The sounder is now an independent instrument on GOES-I and capable of supporting routine operations for the first time. It includes 18 infrared bands. An ozone band is added, more shortwave bands enhance low-level vertical resolution, an accurate split window provides atmosphere-corrected views of the earth surface, and three moisture-sensing bands improve the vertical resolution for moisture sounding. Simulations show that the improved signal to noise achieved by the earth-oriented sounder enables improved coverage of soundings in and around cloudy weather systems as well as improved delineation of vertical variations of atmospheric moisture. Improved soundings in severe storm and hurricane situations are expected to further understanding and improve forecasts of those weather phenomena.

## 9. Additional information

Additional details concerning the GOES I-M system may be obtained by writing to the NESDIS GOES Program Office at the following address.

NESDIS GOES Program Office
Federal Office Building 4
Suitland and Silver Hill Rd
Suitland, MD 20746

Further information concerning GOES I-M and GOES I-M products can be found in NOAA technical reports that are referenced or are being written. They are available from Nancy Everson, NOAA/NESDIS Office of Research and Applications, NOAA Science Center, Washington, DC 20233.

NOAA technical reports expected near the time of GOES-I launch include the following:

- GOES-I Users Guide (GOES-Tap/NOAA PORT)
- WEFAX Users Guide
- GOES-I Data Collection Users Guide
- GOES-I Day-1 Product Descriptions
- GOES I-M Calibration
- GOES I-M Instrument Performance
- GOES I-M Data User Guide (Archive data)

*Acknowledgments.* Contributions to the text by Mike Weinreb (calibration), Kathy Kelly (navigation), and Kit Hayden (sounding) are gratefully acknowledged. Image simulations were performed with the aid of Patrick Dills and Debra Molenar. Sounding simulations were provided by Tim Schmit. Additionally, the many readers who improved the content and wording are also thanked. They are Wayman Baker, Gary Ellrod, Ron Gird, Don Gray, Jamie Hawkins, Roger Heymann, Fran Holt, Keith McKenzie, Don Miller, Richard Reynolds, Henry Schmidt, and Fred Zbar.

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