4.5 Data Regi-tration and Integration Requirements

for

Severe Storms Research

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1. Introduction

Severe storms research is characterized by temporal scales ranging from minutes (for thunderstorms and tornadoes) to hours (for hurricanes and extra-tropical cyclones). Spatial scales similarly range from tens to hundreds of kilometers, depending on the phenomenon being observed.

Sources of observational data include a variety of ground based and satellite systems. As one would expect, requirements for registration and intercomparison of data from these various sources are a function of the research being performed and the potential for operational forecasting application of techniques resulting from the research.

This paper presents an overview of the sensor characteristics and processing procedures relating to the overlay and integrated analysis of satellite and surface observations for severe storms research. It is based on a review of the literature, discussions with meteorologist researchers in the Troposphere Branch of Goddard's Laboratory for Atmospheric Sciences, and on experience in the development of the Atmospheric and Oceanographic Information Processing System (AOIPS).

2. Severe Storm Data Sources

Data sources include geostationary satellites, polar orbiting satellites, radar, aircraft, balloons, and meteorological models. Satellite, aircraft, and radar data are frequently in image form, while the remaining sources and information derived from satellite imagery are either in the form of gridded fields or station observations. This section surveys the major data sources, identifying the information provided and the spatial and temporal characteristics.

2.1 Satellite sources - Geostationary Orbit

The GOES Visible and Infrared Spin Scanning Radiometer [1, 2] (VISSR) provides visible imagery showing cloud structure and patterns, and infrared imagery showing surface and cloud top temperature. A full earth image is generally scanned every 30 minutes, however, limited area north-south scans may be commanded at intervals as frequent as 3 minutes. Analysis of sequences of these images provides meansurements of cloud motion winds and storm growth rates. Spatial resolution is nominally 1 km visible and 8 km IR at the subsatellite point, but degrades away from that point due to curvature of the earth's surface. The IR resolution is approximately 10 km, for example, at 40° latitude. Wind and cloud height observations derived from VISSR are essentially randomly spaced corresponding to locations where cloud features can be identified.

An improved sensor based on the VISSR - the VISSR Atmospheric Sounder[3] (VAS) is currently being operated in a research/evaluation mode. A total of 12 IR channels provide measurements of temperature and humidity integrated over different layers of the atmosphere. When operated in Dwell Sounding mode, all 12 channels are scanned for a selected north-south extent. Because of multiple spin averaging to improve the signal to noise of the radiances, an area the size of the U.S. requires approximately 3 hours to image. Four IR channels may be selected by ground command to scan at VISSR rates (30 minutes for full earth). This multispectral imaging mode provides time sequenced imagery of temperature and water vapor patterns and motion. Like wind fields derived from VISSR, temperature and humidity profiles derived from VAS are generally randomly spaced observations.

Earth location information for the VISSR and VAS data is derived from interactive identification of landmark locations in visible imagery. The initial method used was to fit Kepler orbital elements to direct observations of satellite position and to fit the parameters for spacecraft attitude and sensor geometry to landmark observations.[4,5] In 1975, techniques were developed to derive both orbit and attitude state from image landmarks.[6,7] Chebyshev polynomials are now used to model spacecraft position and image-sun angle as a function of time. This allows predictive parameters to be generated and thus permits earth location of image features immediately after acquisition. The Chebyshev coefficients have been transmitted by NOAA in the image line documentation since 1977.

The VAS navigation procedure correlates prestored 16 x 16 image chips to locate landmarks. Orbit, attitude and camera biases are estimated using an iterative weighted least squares technique.

Comparison of image locations derived using this model with NOAA landmark observations yields the following statistics for residuals:[8]

	mean	σ
pixel	-0.0055	1.335
line	0.0192	1.58

Using 20 landmark observations per day for a 3 day period allows navigation parameters to be extrapolated for 48 hours with 3 pixel accuracy. The mean pixel and line error vs. prediction interval is shown in Figure 1.

2.2 Satellite sources - Polar Orbit

Sensors on-board polar orbiters typically repeat coverage at 12 hour periods. Because this is much longer than time scales of severe storm dynamics, this source of data is not as heavily utilized as the GOES sensors. The primary uses have been model initialization and comparison, extraction of parameters not available from geostationary sensors, and comparison with geostationary observations. Two sensor systems will be summarized here for illustration and comparison.

The Electrically Scanning Microwave Radiometer (ESMR) on Nimbus-6 provides radiometric measurements in two bands for two polarizations. The instrument scans in a 70° area ahead of the spacecraft motion with a constant 50° incidence angle with the earth's surface. Nominal resolution is 20 km cross-track and 45 km along-track. Multispectral classification techniques are used to identify areas of rainfall.[9]

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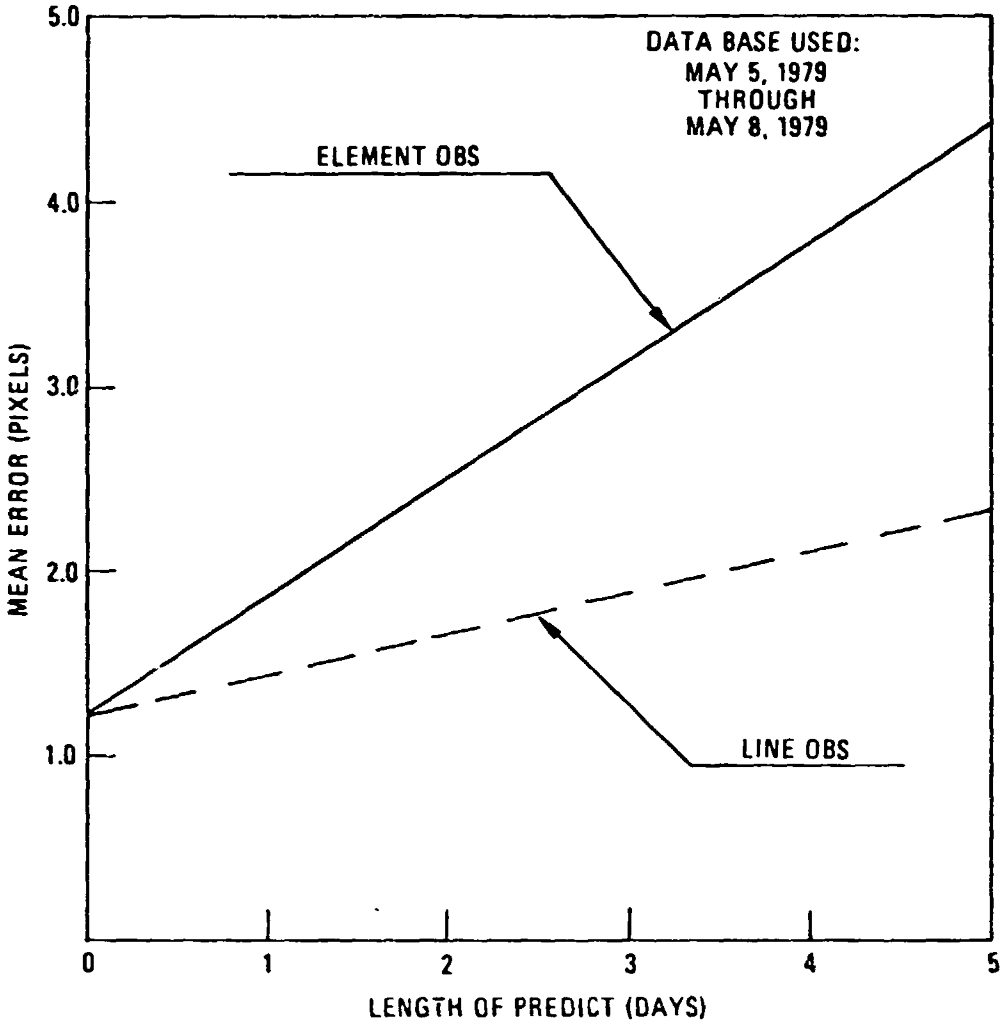

Figure 1. Line and pixel navigation prediction error for GOES VAS.

Four instruments on the TIROS-N and NOAA-6 satellites provide visible and infrared imagery along with sounding radiances.[10]

The Advanced Very High Resolution Radiometer (AVHRR) scans a 1650 km swath in 4 visible and infrared bands. The 1.1 km IFOV is oversampled by a factor of 1.362 to produce 2048 samples per line at approximately 800 meter separation. NOAA generates latitude/longitude values every 40 pixels (51 points per line).

The High Resolution Infrared Radiation Sounder (HIRS/2) scans a 2240 km swath in 20 infrared bands. The 56 step scan produces IFOV's of 17.4 km at nadir, degrading to 58.5 km (cross-track) by 29.9 km (along-track) at maximum scan angle. NOAA generates latitude/longitude values for each scan position.

The Stratospheric Sounding Unit (SSU) and Microwave Sounding Unit (MSU) scan in 8 and 11 steps respectively, resulting in IFOV's exceeding 120 km.

2.3 Aircraft and Ground Based Observations

Aircraft flights are used to measure smaller scale cloud properties and to test new sensors. The scanning resolution depends on the instrument and aircraft altitude. The Cloud Top Scanner, for example, has a 100 meter cross track resolution and a 200 meter along-track resolution. Aircraft navigation data is used to define image georeferencing parameters.

Ground based digital radar provides measurements of rainfall intensity and, for doppler radars, velocity. Digital returns are oriented along radial scans with varying range, range resolution, and azimuth angle resolution. The Norman, Ok. doppler radar for example has a range of 456.2 km, range gate resolution of 0.6 km, and azimuth angle resolution of approximately 0.8°.[11] Elevation angle is varied to provide measurements at different altitudes.

Rawinsonde balloons provide measurements of temperature, altitude, dewpoint and winds at 40 mandatory pressure levels from over 100 stations in the U.S. every 12 hours.

3. Registration Requirements

Data registration processing for severe storms studies tends to have both multi-temporal and multispectral aspects. As mentioned in the discussion of the VISSR, multi-temporal imagery from a single sensor is frequently used to extract measurements of atmospheric motion and cloud growth. The resulting observations are often registered and overlayed on visible imagery from a single time for comparison with cloud features and are registered and integrated with other sources (e.g., ground based observations) for comparison or integration with models. Examples of multi-source image registration include GOES-west to GOES-east for direct stereo cloud top measurements, and digital radar to GOES visible and IR for comparison of rainfall and doppler velocities with cloud structure. These multi-source observations from different times are then registered to produce time lapse displays and temporal analyses. Because of its frequent coverage, its ability to show mesoscale features, and the computional time required to remap sequences of images to a common projection, the GOES imagery is generally used as the reference coordinate system or map base for these analyses. Because of its relative importance, the accuracy and remapping considerations of GOES sensors will be addressed further in the next subsection. Next, some considerations involving point source and gridded field registration will be discussed. Finally, in the next section, the current multi-source combinations will be summarized.

3.1 GOES Data Registration

As described in Section 2.1, the absolute navigation accuracy from current VISSR and VAS landmark processing is on the order of 1 to 2 pixels (1-3 km). Errors may be introduced by:

- operator errors in the identification and correlation of landmarks,

- geometric irregularities in the image, and

- differences between[12] the oblate spheroid model and the actual earth's surface.

For registration of successive image frames, relative errors are typically on the order of a single pixel. In measurement of cloud drift winds, this equates to an error of approximately 0.5 m/sec for 30 minute interval data and 3 m/sec for 5 minute interval data.

Stereo measurements of cloud top heights are made by remapping 512 x 512 image sectors from one GOES satellite to the projection of another. The orbit/attitude coefficients define a (latitude, longitude) to (line, pixel) remapping function and its inverse. This is used to generate a remapping grid, with bilinear interpolation used to relate corresponding locations between grid points. Absolute georeferencing errors are reduced by shifting registered images to align cloud shadows and other features. The resulting relative error is on the order of a $\frac{1}{2}$ pixel, with a resulting absolute cloud height error on the order of 0.5 km.

Digital radar data is registered to GOES Visible and IR imagery through a two step process. Data in radial scan orientation (B scan) is first resampled to an earth latitude, longitude grid. Plane earth, low elevation and short range approximations are used where possible to reduce computation time in transforming from the radar to earth coordinate system. These approximations introduce an error on the order of 0.5 km (one half a GOES visible pixel). Next, the image in this earth latitude, longitude projection is remapped to the GOES projection. Bilinear interpolation is used to compute positions between user specified grid points (usually at 20 pixel spacing).[11]

Polar orbiter data is not generally registered to GOES data for severe storms observations, partially due to the disparate time scales and partially due to the representation of the polar orbiter image location information as latitude, longitude values at sampled locations along scan lines. The latter makes the (line, pixel) to (latitude, longitude) transformation trivial, but makes the inverse transformation difficult to solve. It is therefore easier to register data using the polar orbiter image as a base.

3.2 Point Source and Gridded Field Registration

Point source or station observations (e.g., winds from VISSR, soundings from VAS, and rawinsondes) have known locations and can easily be overlayed on maps or GOES imagery. However, further analysis and comparison with image features frequently requires gridded fields for contouring or diagnostic (e.g., divergence) computation. Furthermore, integrated analysis of multiple parameters requires that all parameters be represented in the same grid locations. A number of techniques are used to interpolate between point source observations to compute values at intermediate grid points. These techniques include weighting values by inverse distance within a search area, eliminating points that are shadowed by closer points, and interactive schemes that recompute weights based on residual errors between original point values and values interpolated from the gridded field. The selection of technique and algorithm parameters affects the degree to which the gridded field represents features in the data.

4.Ø Summary and Recommendations

Current multi-source and multi-temporal registration requirements are summarized below:

Multi-temporal

- GOES VISSR and VAS image frames to first image of a sequence
- Station observations and gridded fields to GOES image loops and to map projections

Multi-source

- GOES VISSR/VAS - west satellite projection to east satellite projection (or the reverse)
- Digital radar to GOES VISSR/VAS
- Station observations and gridded fields to GOES VISSR/VAS

Because the GOES image projection generally serves as a common base, registration accuracy requirements are generally 1 km (1 visible pixel).

Registration of the above data for research case studies generally allows sufficient time for the remapping process. For nowcasting applications as will be performed on the Centralized Storm Information System (CSIS),[13] the registration and overlay must be performed in minutes.

While the above capabilities for data registration are fairly powerful, limitations still exist:

(1) Absolute errors on GOES VISSR image are as high as 6 pixels. It is not clear whether improved models or procedures can improve this. Furthermore, non-linearities are observed in short interval images that are not found in 3Ø minute data and are therefore not modeled in the navigation function.

(2) Stereo GOES image pairs are currently offset interactively to compensate for absolute navigation errors. Registration using relative control points in the two images may improve the registration accuracy and thus the accuracy of cloud height measurements.

(3) The incorporation of a new data source (e.g., a polar orbiting sounder) into an analysis requires the development of additional software to identify and extract image control points and to perform the necessary resampling and remapping to the reference map projection. It is also extremely difficult to experiment with map projections, resolutions, and resampling functions. An interactive "geographic information system" is needed that allows selection of map projection, resolution, data sources, and resampling function for each source. Image georeferencing function implementations are needed for different data sources that embody approximations for computational efficiency while maintaining required geographic accuracy. Finally, the system interface should provide for straightforward addition of new sources in terms of format and image location parameters.

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