GATES - a small, agile imaging satellite prototype for GOES-R

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ABSTRACT

By using current technology, it appears possible to build and launch a prototype for an advanced geosynchronous imager on a small satellite within a few years. This could be done independently of upgrading the other GOES mission functions of atmospheric sounding, communications, and space- and solar-monitoring.

At NASA-GSFC, we are engaged in a feasibility study for a Geosynchronous Advanced Technology Environmental System (GATES). GATES is envisioned as a high performance imager on a small dedicated satellite with a complete ground system. GATES could fly in the era of the Earth Observing System (EOS, circa 1999-2004 AD) and serve as a prototype for NOAA's next generation of operational satellites (GOES-R, circa 2008 AD). In addition to carrying all the channels identified for NOAA's GOES-R Imager, GATES is being designed to carry all the broadband channels specified for NASA's Moderate-resolution Imaging Spectro-radiometer (MODIS) instrument on the EOS platforms. This channel complement gives GATES the capability to fill in the space-time gaps in cloud observations from polar-orbiting satellites and to serve as a cross-reference between polar radiometers.

Multispectral rapid-imaging requirements are met by using several recently developed technologies -- large detector arrays with active cooling, star-tracking and gyroscopic attitude-determination, a small and rigid spacecraft, a heat-resistant telescope, a phased-array Ka-band downlink, realtime digital image rectification, and Internet data distribution on the ground. The GATES design is so small and agile that it could use the momentum wheels to scan the entire spacecraft back-and-forth across the Earth.

Keywords: spacecraft, imaging, GOES, GATES

1. INTRODUCTION

Global weather and climate operations and research benefit from the national observatories in geosynchronous orbit, such as the USA's GOES-8 and GOES-9 spacecraft. Both NASA and NOAA benefit from the ability to monitor rapidly changing cloud and moisture fields in the western hemisphere. NOAA has identified the need to improve on the GOES weather monitoring capabilities in their weather observing requirements for a next-generation GOES-R[1] Imager (circa 2008 AD). These requirements call for roughly doubling the capabilities (channels, resolution, and coverage rate) of the current GOES-8 Imager. Climate research could also benefit from an improved geosynchronous observing platform by observing the diurnal cycle with greater precision and with spectral bands tailored to climate studies.

We believe the technology now exists to develop an imaging system that can meet both weather and climate needs. However, due to the level of technological challenge and risk involved, developing such an imager as part of the operational GOES program could be a significant gamble, risking program schedule, cost, and continuity of data delivery. For example, there were serious programmatic and engineering difficulties experienced with GOES-I in the early 1990's, when trying to convert the AVHRR heritage to fly on a 3-axis semi-stabilized satellite. GOES-8, the first satellite in the current operational series, required over one year of on-orbit characterization and software corrections to develop adequate pointing and radiometric performance. That experience made it clear that the next generation geo-imager should be first prototyped with a flight model to minimize risk and expense to an operational series. A prototype provides the opportunity to correct any shortcomings which are discovered in orbit, before flying the operational model.

To meet this need, we propose a synergistic design for a complete geostationary atmospheric imager with state-of-the-art radiometric qualities. This imager is envisioned to fly on a small dedicated satellite in the era of the Earth Observing System (EOS, circa 1999-2004 AD) with its own complete ground station, and serve as a prototype for NOAA's next generation of operational satellites.

The advanced geo-imager is distinct from NOAA's entire GOES program, and so it is called the "Geosynchronous Advanced Technology Environmental System" (GATES). The word "System" is used because GATES is more than just an instrument -- it is an autonomous satellite that also includes a ground system for command-and-control and for data processing-and-delivery to scientific users. GATES will act as a proving ground on which NASA can wrestle with the technological difficulties of meeting the science and operational requirements using the latest available technologies without the fear and consequent expense of jeopardizing the operational GOES system. In addition, while on orbit, GATES will be a state-of-the-art national geo-observatory, capable of providing unsurpassed weather and climate data.

2. CONCEPT DEVELOPMENT

2.1 New Millennium Technologies

In 1995, NASA reviewed the latest high technology items for its New Millennium program. That review identified a number of enabling technologies that are now available for purchase, including:

- mechanical cooling of optics and detectors
- large focal plane arrays
- sun- and heat-resistant optics
- precise star-trackers and gyros
- high-speed data handling and mass storage on-orbit
- lossless data compression
- Ka-band downlinks for high data rates
- efficient solar arrays and batteries
- autonomous spacecraft
- a selection of geosynchronous launchers
- efficient command-and-control rooms
- realtime image data processing
- fast client-server data access systems on a national and global scale

So many enabling technologies inspired a concept study for an advanced geo-imager.

2.2 Goals for an Advanced Geo-Imager

The most important scientific and operational goals are to capture the rapidly changing weather and the diurnal climate patterns:

- clouds: location, height, amount, and phase
- water vapor: high and low amounts and motion in the troposphere
- surface conditions: temperature, vegetation and soil moisture
- transient events like fires and volcanoes
- survey the entire hemisphere several times per hour
- observe severe storms many times per hour
- operate 24 hours per day, despite eclipses and solar loading near midnight
- design life of 5 to 7 years

2.3 Design Objectives for an Advanced Geo-Imager

Geosynchronous and polar orbits can be complementary in their coverage of the Earth. In particular, a geo-imager equipped with the proper spectral bands can fill in the gaps of the space-time coverage by the polar orbiting imagers, thus providing direct measurement of the rapid variations in water vapor and cloud cover that polar imagers would otherwise miss. A geo-imager can also serve as a cross-reference between polar imagers providing continuity of calibration.

It is important to recognize, however, the challenges of geosynchronous orbit, which is approximately 50 times farther from the Earth's surface than the polar-orbiting weather and climate satellites. At that distance, pointing and horizontal resolution is 50 time more difficult, and the radiant flux is 2500 times less than in low-earth orbit. These factors constrain a fast geosynchronous radiometer to use relatively broadband channels in order to gather enough light, and to use accurate knowledge of orbit and attitude to earth-locate images. In addition, every 24 hours, the sun appears in or near the field-of-view of a geosynchronous Earth-pointing instrument, causing very significant optical and radiometric difficulties.

Keeping these issues in mind, an advanced geo-imager should:

- be simple, reliable, and unaffected by diurnal solar loading
- complement the polar orbiting systems
- use broadband spectral channels to gather sufficient flux
- have many detectors with high signal-to-noise and low drift rates
- have an accurate calibration scheme
- use a fast, dedicated downlink
- use precise knowledge for pointing and registration
- register and geo-locate every pixel in realtime
- perform realtime data processing and distribution to weather forecasters
- scan the earth frequently enough to track the local diurnal cycles over the hemisphere
- archive data to mass storage for climate re-analysis
- fly an operational prototype for at least one year to test diurnal and seasonal behavior

3. IMAGING REQUIREMENTS

The design of an advanced satellite imager is driven by requirements for multiple bandpasses with good signal-to-noise at high spatial and spectral resolution. For time-lapse animation of weather events, one needs wide area coverage with frequent updates remapped to earth-coordinates. For realtime forecasts, high speed data processing and distribution is required.

3.1 Space-Time Requirements

NOAA's space-time requirements (draft) for GOES-R[1] are listed in Figure 1. The resolution and refresh rates required by GOES-R imply data rates more than an order-of-magnitude larger than the current low-frequency S-band downlinks from GOES-8, especially since the datarates in colmn 3 add together.

Region, NS x EW km x km	Duration min	Data rate, vis. Mbits/sec	Purpose	Refresh frequency scenes/hour
1000 x 1000	<1	>3	mesoscale (storm)	>60
3000 x 5000	<5	>8	regional (USA)	>12
12000 x 12000	<15	>25	hemisphere	>4

Figure 1: NOAA's space-time requirements for GOES-R imaging (1994 draft).

In addition, NOAA requires operational robustness:

- independent mesoscale and hemispheric imaging
- ±1 km navigation and registration
- 24-hour service, through eclipse
- minimal outages for maneuvers and housekeeping

3.2 Radiometric Requirements

If we combine NOAA's draft of its imaging radiometric requirements for the GOES-R[1] era (2008 AD) with the most effective Imager and Sounder channels on GOES-8, and then add the NASA-NOAA specifications for the MODIS[2] broadband channels, we arrive at the list of bandpasses, signal/noise and horizontal resolution requirements shown in Figure 5. The radiometric specifications and main data products from each band have been established by a myriad of previous GOES, POES, GEO and EOS committees.

Figure 6 presents the GOES-8, GOES-R and GATES bandpass specifications graphically. The bands are compared to a sketch of the Earth's transmittance spectrum from the solar shortwave to the thermal longwave bands. The GATES bands occupy all of the atmospheric windows, splitting them where differential radiances are a reliable measure of the total column property of that atmosphere. The cluster of absorption bands in the 6 to 8 micron spectrum is planned for tracking water vapor as a function of height.

The many additional MODIS bands shown in Figure 5 and Figure 6 are not a significant burden on top of the GOES-R bands because the optics and focal planes required for the GOES-R bands are already in place. Only the detector population occupying the optical-mechanical design doubles, not the design itself.

In addition to the union of the GOES-I, GOES-R and MODIS channels, it would be very useful to add a blue channel between 0.45 and 0.50 microns to monitor dust and haze, since it is now recognized that aerosols are as important in controlling the radiation budget as carbon dioxide, water vapor, and clouds. This blue channel could be accommodated with little effort in the visible focal plane. The blue channel is included in Figure 6, indicating that the conceptual design of GATES is still open to modification.

4. CONCEPTUAL DESIGN

To achieve high spatial resolution over the western hemisphere in a short time, we require many detectors spanning a wide field-of-view. Global coverage can be achieved by scanning "tall" pushbrooms of detectors having N-S nadir projections of 1000 km in height. At geosynchronous altitude, this corresponds to a full-height field-of-view of 1.6 degrees, comparable to MODIS. Using this tall pushbroom, one can scan the entire Earth in twelve back-and-forth east-west sweeps, or scan a local storm in a single east-west sweep. Finally, global and local scans can be interlaced to achieve simultaneous synoptic and mesoscale coverage, as desired by the National Weather Service (NWS). Some of these scan strategies are illustrated in Figure 2.

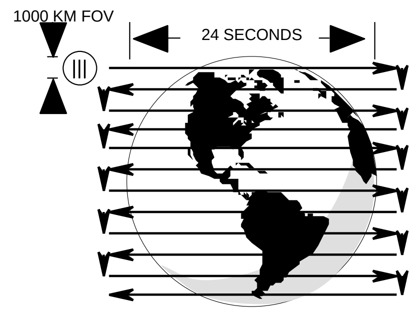
Because GATES is a small, agile dedicated satellite, it is possible to execute the pushbroom scans by slewing the entire satellite, thus eliminating the more traditional scan mirror. This requires a rigid design, probably with stationary solar arrays. Initial analysis shows that the satellite scanning motion can be performed using available wheel technology.

The effects of solar intrusion are minimized by doing away with the traditional exposed scan mirror, and by using a easily baffled off-axis telescope. The telescope can be made of silicon carbide or composites for low thermal expansion and good resistance to solar heating, and can be well monitored with thermistors to characterize and correct radiometric calibration variations over the course of the diurnal cycle.

Low noise performance will be achieved using a mechanical cooler for the thermal bands. It is expected that a temperature on the order of 65K will be targeted.

FULL DISK: <10 Minutes

(GOES I-M: 26 minutes)



<15 Minute Full Disk with 1 Minute Local Storm

(GOES I-M: Not Possible)

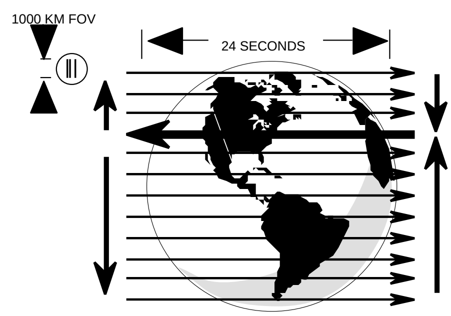


Figure 2: Some scan strategies available for synoptic and mesoscale coverage using a tall pushbroom scanner at geosynchronous station.

Radiometric calibration is always a difficult issue for a radiometer that has both shortwave (solar) and longwave (thermal) bands. Consequently, we aim to have more than one calibration strategy:

- on-board thermal absolute and relative calibration
- absolute and relative calibration using the sun through a pinhole array
- relative calibration using the moon
- surrogate calibration with respect to the polar orbiters

Lunar and solar calibration are possible because GATES is a small, agile dedicated satellite that can be pointed anywhere in the sky using momentum wheels.

The large number of bands and the high ground coverage rate will require the use of fast on-board data buffering and data handling, lossless data compression, and a high-frequency Ka-band downlink to move the pixel stream to the ground.

5. SCIENCE CAPABILITIES

Only geosynchronous orbits provide a way to directly measure the rapid changes in cloud and surface conditions which occur every day. Figure 3 compares the data products available from a simple 3-channel "stormsat" like GOES-7, to GOES-R and to GATES. GATES shows a distinct advantage for monitoring climate and land processes, which NOAA can expect to have under its stewardship when the US Global Change monitoring program becomes operational early in the next century. Because GATES is still in the conceptual phase, the list in Figure 3 is only an outline of a science plan. Fortunately, the GOES-R and MODIS science teams have done their homework, and they will be in place when and if GATES flies.

WEATHER		
3-CHANNEL STORMSAT	**8-CHANNEL GOES-R**	**17-CHANNEL GATES**
High res. clouds, Cloud-track winds, 300 mb water vapor, High-level winds, Cloud top temp., Convective vigor	High res. clouds, Cloud-track winds, 300 mb water vapor, High-level winds, Cloud top temp., Convective vigor, Cloud/snow diff., Winds in winter, Surface/fog diff., Aviation weather, 500 mb water vapor, mid-level winds, Split window (H2O), total water vapor, CO2-sliced cloud top, ASOS supplement	High res. clouds, Cloud-track winds, 300 mb water vapor, High-level winds, Cloud top temp., Convective vigor, Cloud/snow diff., Winds in winter, Surface/fog diff., Aviation weather, 500 mb water vapor, mid-level winds, Split window (H2O), total water vapor, CO2-sliced cloud top, ASOS supplement, water/ice cloud top, cloud phase processes, Split window (N2), Boundary layer temp., 700 mb water vapor, low level winds
CLIMATE AND LAND		
3-CHANNEL STORMSAT	**8-CHANNEL GOES-R**	**17-CHANNEL GATES**
	• Split window (H2O), Total water vapor, fires	• Split window (H2O), Total water vapor, water/ice cloud top, cloud phase processes, Split window (N2), Boundary layer temp., 700 mb water vapor, low level winds, Vegetation, bio-status Americas, Cirrus, Greenhouse process, Split window (H2O), fires, Total Ozone

Figure 4: Comparison of the kind of data products from some proposed geosynchronous Imagers.

6. DATA PROCESSING AND DELIVERY

GATES can generate a firehose of data, comparable to MODIS, for the same reasons. We expect that the Ka-band downlink form GATES would go to a central processing system that would calibrate and rectify the multi-channel imagery. We expect to distribute the imagery and selected data products using high speed land lines and protocols, as sketched in Figure 4.

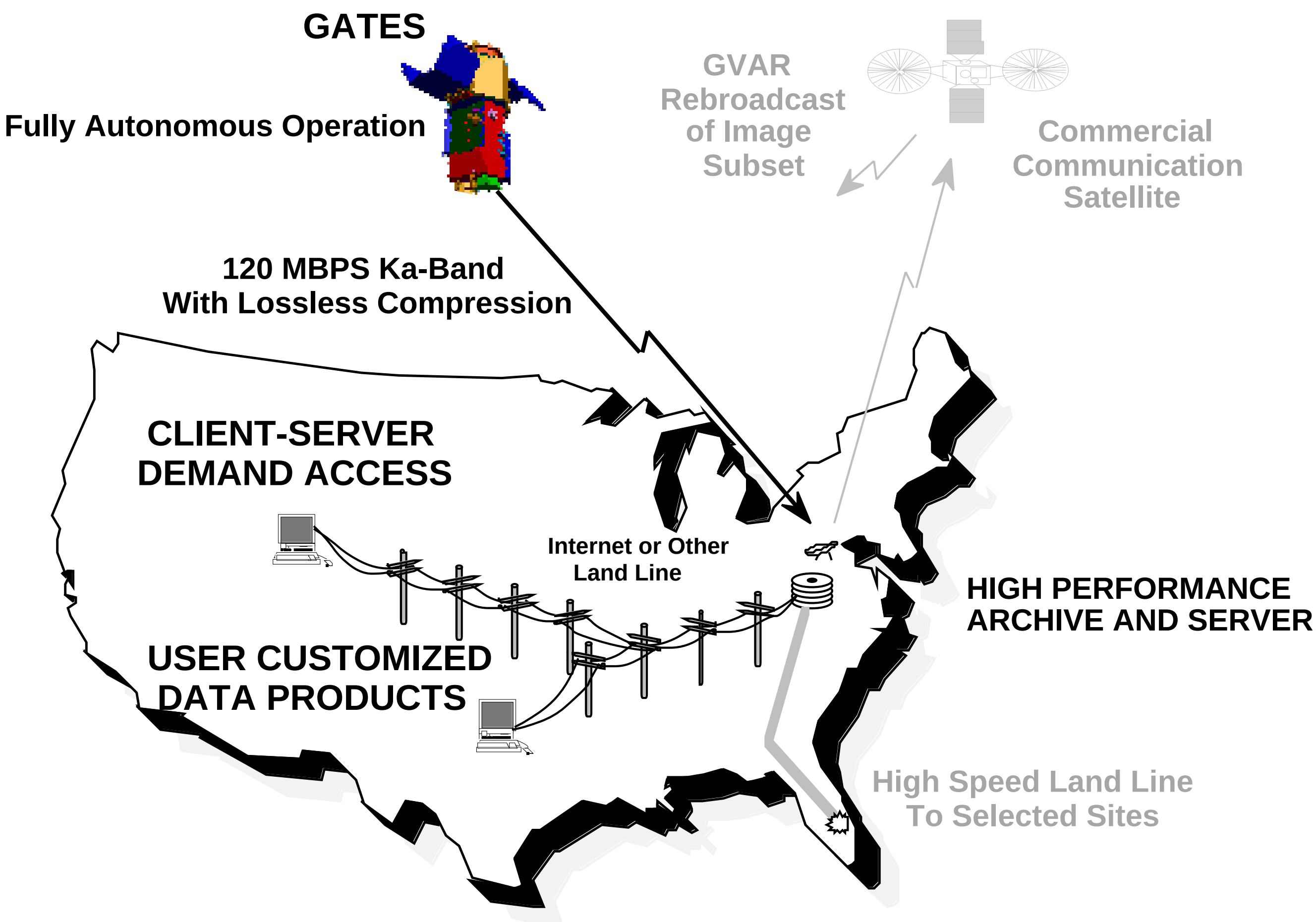


Figure 4: Ka-band downlink and landline data distribution concept for GATES.

Client-server architecture and predefined custom products will deliver timely images to remote weather forecasting sites, using the high-speed national ATM network that should be in place by the turn of the century. In addition, we could re-create the GOES-8 GVAR data format for broadcasting 5-channel imagery through old GOES or through commercial satellites to operational NOAA and private users during the GATES demonstration

7. SUMMARY

GATES could meet or exceed NOAA's draft GOES-R imaging requirements

- 17 channels merging GOES and EOS science
- excellent S/N and NEDT performance
- 0.5 km vis, 1 & 2 km IR effective ground patch sizes
- ground registration to 1 km
- operate through local midnight and eclipse
- full disk in ≤ 10 minutes
- full disk in ≤ 15 minutes with simultaneous 1 minute storm coverage

Compared to the GOES-I/M Imager

- 3x number of channels
- 5x faster coverage
- 2x higher spatial resolution
- up to 2x lower noise

8. ACKNOWLEDGMENTS

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9. REFERENCES

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