MEDIUM EARTH ORBIT (MEO) AS A VENUE FOR FUTURE NOAA SATELLITE SYSTEMS

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ABSTRACT

Low Earth orbits (LEO) and Geostationary Earth orbits (GEO) orbits have traditionally been the venues of choice for observations, albeit for very different reasons. LEO provides high spatial resolution with low temporal resolution while GEO provides for low spatial resolution, but high temporal resolution. NOAA utilizes both venues for their environmental satellites. The NOAA Polar-orbiting Operational Environmental Satellites (POES) reside in LEO Sun synchronous orbits at approximately 830 km in altitude, as do the Defense Meteorological Satellite Program (DMSP) satellites of the Department of Defense. In the near future the POES and DMSP satellites will be merged into a new satellite system referred to as the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The NOAA Geostationary Operational Environmental Satellite (GOES) system, as the name specifies, resides at the other preferred observational venue of GEO. The Jet Propulsion Laboratory (JPL), under contract to NOAA, has been studying the characteristics of medium Earth orbits (MEO), at altitudes between 1000 and 35,800 km, as an observation venue to answer the question as to whether MEO might capture the attributes of the two traditional venues. This on-going study initially focused on determining the optimal altitude for MEO observations, through numerous trade studies involving altitude, instrument complexity, coverage, radiation environment, coverage, spatial and temporal resolution, revisit time, data rates, data latency, downlink requirements and other parameters including cost and launch complexity. Once the optimal altitude of 10,400 km had been determined, the study proceeded to explore single and multiple MEO satellite constellation performance capabilities using two instrument types, a visible through infrared (IR) imager and IR sounder as the satellites' payload. MEO performance capabilities were compared to comparable LEO and GEO satellite constellation capabilities. This portion of the study concluded that indeed for global coverage a constellation of satellites operating in the MEO venue could capture the attributes of those operating in the LEO and GEO venues. Three 8-satellite constellations configurations – Walker, ICO, and Equatorial-Polar (EP) – then were studied to develop more constellation coverage statistics including robustness to individual satellite failure. That study phase concluded that the EP constellation was superior to both the ICO and Walker configurations.

1. INTRODUCTION: THE CURRENT CONFIGURATION

The National Oceanographic and Atmospheric Administration (NOAA) operational environmental satellite system is comprised of geostationary satellites for short-range warning and polar-orbiting satellites for longer-term forecasting. The Geostationary Operational Environmental Satellite (GOES) system maintains a continuous data stream from two satellites, one located at 75 West latitude and the other at 135 W latitude, in support of National Weather Service (NWS) requirements, transmitting weather data, and visible and infrared images covering the regions of the world from approximately 20 W longitude to 165 East longitude. Each satellite's imagers have the additional capability to focus on narrow regions of the globe, such as to obtain maximum coverage of a hurricane. The Polar Operational Environmental Satellite (POES) system provides daily global coverage, with morning and afternoon low earth orbits that deliver data such as cloud cover, storm location, temperature, and atmospheric heat balance for improved weather forecasting. Additionally, the Defense Meteorological Satellite Program (DMSP), run by the Air Force Space and Mission Systems Center, is used for monitoring meteorological, oceanographic, and solar-terrestrial physics environments. The future National Polar-orbiting Operational Environmental Satellite System (NPOESS) and its managing Integrated Program Office (IPO) were established in 1994 to converge existing multi-agency polar-orbiting satellites (POES and DMSP) into an integrated national program that will be used to monitor global environmental conditions, collect and disseminate data related to weather, atmosphere, oceans, land and the near-space environment. NPOESS launch readiness is scheduled for 2009, with launches for a fully operational system planned through about 2016.

2. AN ALTERNATE VIEW

As part of an ongoing system architecture study, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Office of Systems Development (OSD) and the Jet Propulsion Laboratory (JPL) are providing input to the NOAA development process for an environmental observing system that would potentially follow the GOES-R series, scheduled for launch readiness in 2012. OSD manages the NOAA operational geostationary and polar-orbiting environmental satellite programs, provides spacecraft, launch services, and ground systems, and is responsible for defining user requirements and developing designs of future satellite systems to meet those requirements (Gerber, et al., 2004; Kidder and Vonder Haar, 2005). A long-term goal of the relationship between NESDIS and JPL is the investigation of the merits of combining the capabilities of the low earth orbit (LEO) and geostationary earth orbit (GEO) satellite systems into a consolidated medium earth orbit (MEO) system, which would provide global near real time weather data everywhere, anywhere, all the time.

The study suggests that a MEO satellite constellation may afford the greatest potential for providing NOAA with the most cost-effective path to the high spatial, temporal, and spectral resolution environmental data it needs to achieve its 21st century strategic plan. The plan recognizes the increasing linkages between the environment, the economy and public safety with an implementation goal of transitioning from individual polar and geostationary observational programs to an integrated system that meets current and future observational, processing and communications requirements. MEO architecture provides advantages in spatial coverage, global temporal revisit times and communications infrastructure. The continued optimization of the MEO architecture includes consideration of the data collected by other Earth observing systems and platforms, both nationally and internationally, and recognizes the increased widespread interest in implementing an integrated global earth observation strategy.

Furthermore, the architecture study is driving the need to understand more comprehensively the science requirements from the broader ocean and atmosphere communities, towards providing a complete global weather monitoring system for long-term climate and environmental observations and contributing to the international Global Earth Observation System of System (GEOSS). These requirements are being used to define instrument suite options for a potential MEO demonstration mission in the 2012-2013 timeframe. The study process also identifies new sensor needs that would drive technology planning, investment and development.

3. CONSTELLATION ARCHITECTURE STUDY

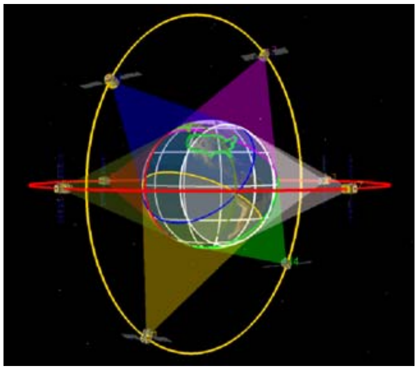

Figure 1. Equatorial-Polar (EP) Constellation

Three different constellations were selected for this study. The Equatorial-Polar (EP) constellation configuration (Figure 1) was selected for its ability to support ease of migrating the GOES GEO equatorial satellites and NPOESS LEO polar satellites into a MEO EP configuration. The Walker (Figure 2) was selected because of experience with the Global Positioning System (GPS) and ICO (i.e. Intermediate Circular Orbit, as for communications satellites), (Figure 3), was selected because of its excellent communications coverage. Numerous tradeoff studies were performed to evaluate each constellation with respect to its imaging and sounding coverage,

coverage robustness (primarily for CONUS) under satellite failure conditions and inter-satellite and downlink communications complexity.

3.1. Orbit Altitude and Inclination Selection

For years MEO orbits have been, for the most part, unattractive due to the belief that the Van Allen radiation belts create a radiation environment unsuitable for satellites. As part of this study JPL revisited this issue and performed extensive analyses of this radiation and the effects of shielding. Figure 4 summarizes our analyses of the radiation environment and Figure 5 shows the effects of shielding. The GPS constellation, at an altitude of 20,200 km, was selected to represent the MEO radiation environmental limit not-to-be-exceeded. The analysis shows that the environment is altitude dependent as well as inclination dependent. Trade studies were directed at maximizing coverage and spatial and temporal resolution while minimizing the yearly total dose. Studies concluded that the optimum altitude was 10,400 km, and that inclinations between approximately 20 and 50 degrees should be avoided. The EP has two obit plane inclinations, namely 0 and 90 degrees, thus producing the lowest radiation environment for that constellation when compared to the Walker and ICO, which are both at 57degrees, the traditional inclination of choice for these two constellations. This puts the Total Integrated Dose (TID) for the Walker and the ICO constellations at approximately 3.7E+4 RADs (radiation) behind 5mm of aluminum shielding. Shielding ray trace analysis, which takes into account all the aluminum between the electronic component and the outside environment, generally shows that there is at least 7.5mm of aluminum shielding. If we extend that in the satellite design to

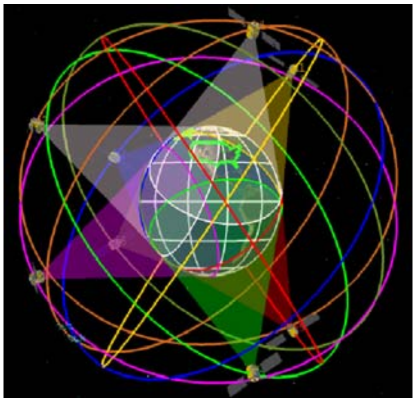

Figure 2. Walker Constellation

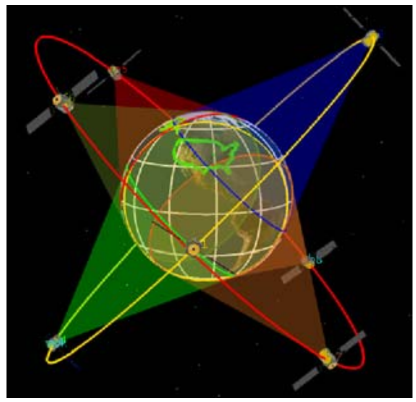

Figure 3. ICO Constellation

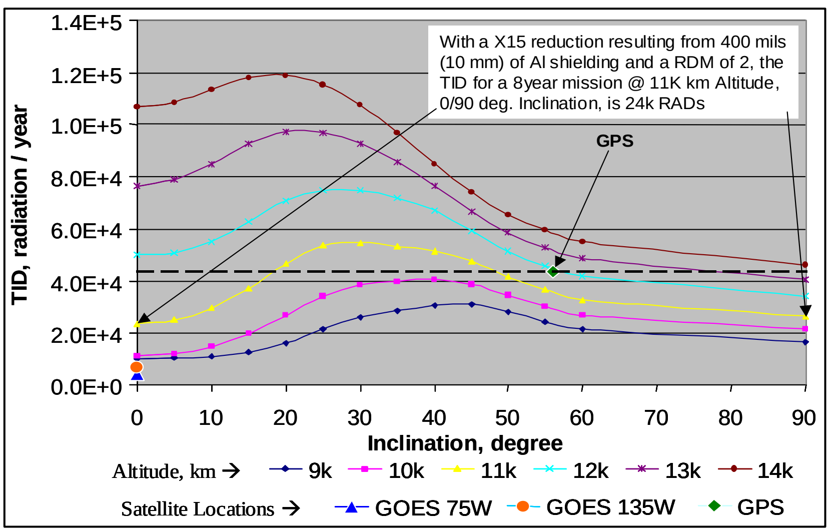

Figure 4. Annual TID received by a silicon chip with 5mm aluminum shielding (calculations based on solar maximum conditions).

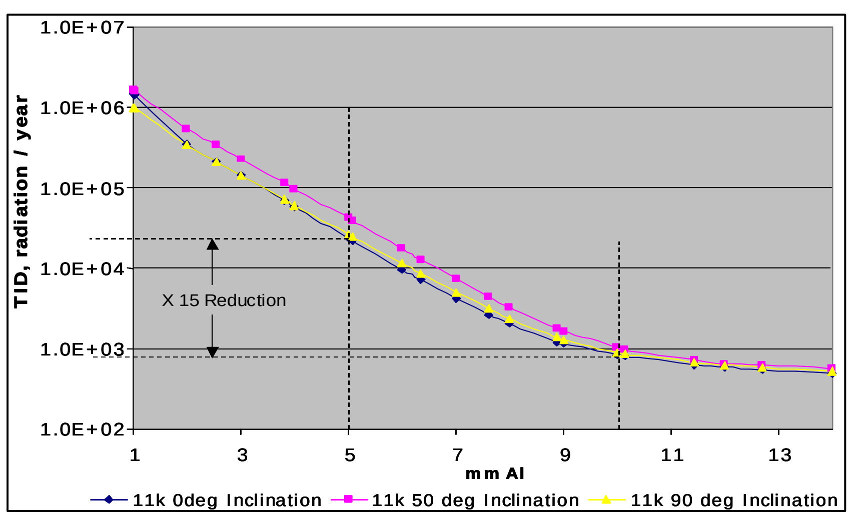

Figure 5. TID attenuation vs. aluminum (Al) shielding

achieve 10mm, Figure 5 shows that a reduction of 15 in TID can be achieved. For any of the constellations studied, if 3.7E+4 TID per year from Figure 5 is used as the maximum TID behind 5mm of aluminum then applying a radiation dose margin (RDM) of two, 3.7E+4 TID becomes 7.4E+4 per year to shield against. 8 years of satellite operation in this environment raising the TID to 5.9E+5. If an additional 5 mm of shielding is added to the 5 mm we already have, the 5.9E+5 TID is reduced by a factor of 15 or 39.3E+3 TID, not an unreasonable number since many LEO satellites using Mil Std 883B and screened commercial parts achieve 30E+3 RADs TID capability. The equivalent TID for the EP constellation is 24E+3 TID. To summarize, MEO satellites with a planned 8-year operational life must be designed such that their electronic parts, at the silicon level, have at least 400 mils (10mm) of Al between them and the natural environment.

Analyses of GOES instruments very much like the Advanced Baseline Imager (ABI) Sounder were performed by Gerber, et al. (2004). Table 1 summarizes, in a qualitative form, the results of these analyses with the conclusion that the EP constellation provides the most robustness of the 3 constellations studied.

Constellation Configuration	Coverage Imaging/Comms	Coverage Sounder	Robustness (CONUS)	Inter-Sat & D/L Comms Complexity	Ease of Migrating From GEO-LEO Configurations
EP - 8	Excellent	Fair	Very Good	Moderate	Excellent
Walker - 8	Good	Very Good	Good	Difficult	Poor
ICO - 8	Excellent	Very Good	Very Good	Moderate	Poor

Table 1. MEO implementation of GOES auxiliary communications, imaging, sounding, and robustness analysis summary and ranking.

3.2. Communications

Broader bandwidth communications are needed as a result of higher resolution global coverage and temporal availability, with an approach that reduces the resource load on satellites in order to support the primary function of data collection. Three options for MEO communications architectures were evaluated.

Option 1 consists of a distributed high-speed ground network with commercial rebroadcast, with upgraded SafetyNet sites and ground network, and with medium data rate rebroadcast. Option 1 is namely a modified NPOESS SafetyNet (see Figure 6) with commercial rebroadcast, using Ka-band downlinks from the individual satellites using mechanically steered parabolic antennas. This option calls for much higher data rates and extensive network upgrades. Commercial satellites would be used for data rebroadcast (e.g. AWIPS-like broadcast), recognizing that commercial GEO satellite transponders provide regional coverage but such coverage is satellite specific and limited for oceanic and low population regions. The rebroadcast data rate is limited, albeit about 25 times higher than the current GOES rebroadcast network, but orders of magnitude lower than the instrument data collection rate. Option 2 comprises optical satellite crosslinks to a downlink satellite with a Ka-band data downlink to a single ground node and a client-server data redistribution network (e.g. no network of ground stations). Onboard processing for routing data satellite-to-satellite would be needed, increasing satellite resources (e.g. power and mass). The satellites would exchange their observational data and satellite health and safety data with each other and with ground-based receiving stations in real-time. The data rates for ground redistribution are limited, but each user gets data as requested; cost scales with the number of GOES

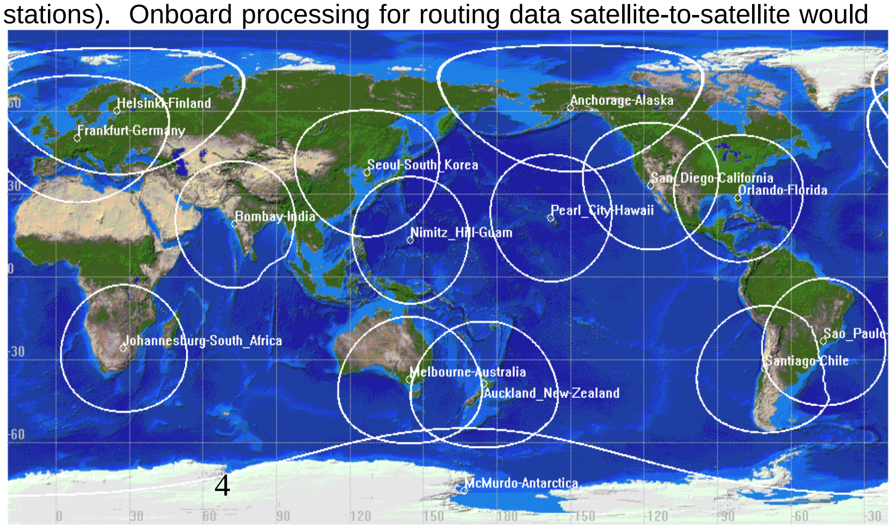

Figure 6. NPOESS Ground Network Map.

rebroadcast clients. Option 3 consisted of optical satellite cross link with hybrid data redistribution, using medium data rate rebroadcast and a client-server ground network. The constellation of satellites would be capable of broadcasting data to system customers, including both data that have been processed on the ground and data that originate at the satellites.

4. PATHWAY TO THE FUTURE

A pathway to a full EP constellation can be viewed in three steps. Beginning with the present constellation, the first step is to launch a demonstration mission into an over-the-pole orbit. The next is to fill out the polar plane by adding three more MEO satellite and spacing them equally. The final step is to place four MEO satellites in the equatorial plane to complete the full EP constellation.

The demonstration mission would place one MEO satellite in a 90 degree inclination over-the-pole orbit. Such an orbit offers a number of opportunities to demonstrate the concept, perform risk reduction, check out instrument concepts and data flow issues, and test and validate instrument scanning strategies. Instrumentation would consist of an imager and infrared and microwave sounders.

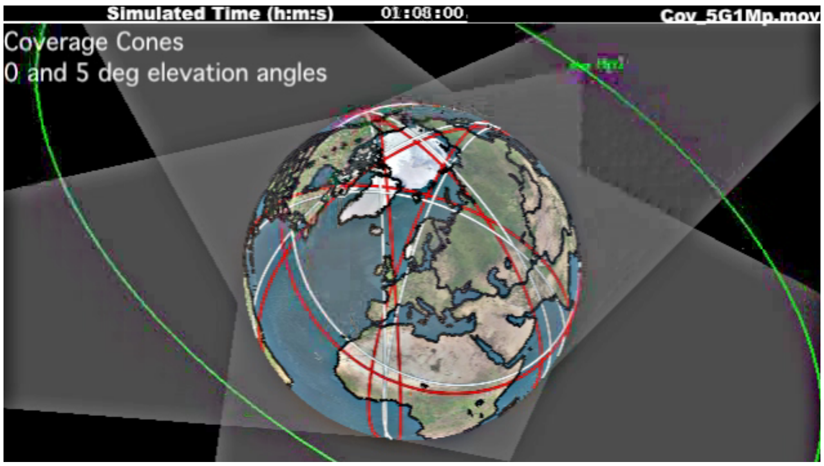

Figure 7. Coverage from a single MEO satellite complementing the International Geosynchronous satellite systems. Elevation angles are shown for 0 degrees (red) and 5 degrees (white).

For the North and South Poles and parts of Northern Europe the MEO would be available to take data continuously for 2 to 2 ½ hours (the higher number would be for a point exactly under the orbit track) out of every 6 hour orbit, giving four data periods of perhaps 15 minute interval data throughout the day. Figure 7 shows coverage for a one polar MEO demonstration. Numerical models would be able to test the advantages and benefits of having high fidelity, rapid-repeat vertical profiles of winds, temperatures, and moisture in cloudy and clear areas during four periods daily. Data from the demonstration mission would be very useful for examining varying look angles and resolutions at a point, and providing polar wind demonstration. Further, such a data stream would compliment data from existing and planned international geostationary systems by filling in the gap over the poles.

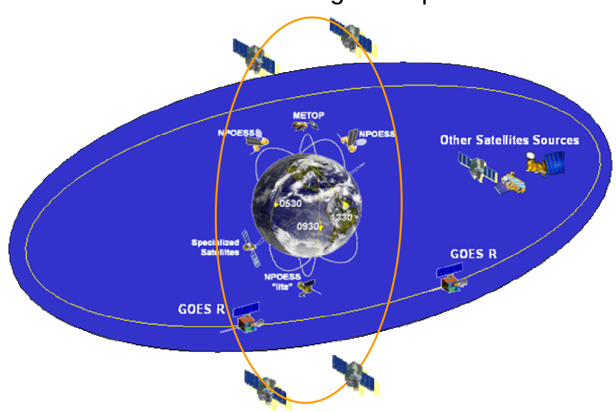

Figure 8. Diagram of four MEO satellites in an over-the-pole plane along with two of the nearly half dozen international Geosynchronous systems.

By adding three more MEO satellite to the same 90 degree orbit plane and spacing them equal distances apart, continuous polar data would be available as a point is viewed first by one MEO satellite, then by the next one, then the next one, and so forth, all with overlap (Figure 8). For the first time, there would be full global coverage, meaning the full four-pi steradians of the globe. There would be a continuous data from anywhere, all the time, in real time – a substantial contribution to the Global Earth Observation Systems of Systems (GEOSS).

If one of the four satellites should fail, the remaining three could be re-phased to a spacing of 120 degrees apart and still acquire almost continuous data until a replacement MEO can be launched.

5. DEMONSTRATION MISSION

5.1. Rationale

The rationale for a MEO demonstration mission is to validate that basic imaging, temperature sounding, and wind and liquid/solid water profile measurement requirements can be met from 10,400 km MEO altitude and provide a communications backbone for a variety of NASA, NOAA, and NPOESS IPO missions. The overarching purpose of such a mission would be to demonstrate a sustainable, extremely capable system that is superior to current implementations and affords significantly reduced long-term costs compared to other implementations that could deliver similar data products and capabilities. Recognizing that observational requirements dictate temporal resolution, spectral coverage and resolution, spatial resolution and radiometric performance, an objective of the study is to provide definitive studies and trades as input to roadmaps for MEO and other satellite constellation options for NESDIS OSD.

An evolutionary MEO road map to a post-GOES-R observational capability must support continually improving weather predictions, plus climate and environmental assessments and forecasts, with near real-time data availability, total global coverage, 0.5 km at 0.5 microns instantaneous geometric field of view or better spatial resolution, improved spectral coverage (including microwave for cloudy weather conditions) and globally consistent, long-term accurate and stable data collection. Based on architecture studies performed by JPL to-date, an EP MEO demonstration system could be developed to serve three functions: (1) to demonstrate MEO-observing capabilities with GOES-like instrumentation, (2) to provide an operational communications system, and (3) to provide a risk retirement test bed for evaluating new instruments developed to exploit MEO opportunities and provide NOAA a cost-effective, risk-reduction path for developing environmental observation instruments for future orbital and ground systems architectures.

The MEO demonstration plan calls for launching a satellite augmenting the capabilities of GOES-R, other meteorological satellites and NPOESS while continuing the usage of NPOESS for the Polar Regions. Furthermore, it provides a platform for validating/demonstrating new instruments to substantially improve the environmental data collection and weather prediction capabilities of NPOESS and GOES-R, such as an advanced optical and infrared imaging and sounding and a high-performance microwave radiometer/sounder with spatial resolution of the order of 1 km at 15 microns and 50 km respectively.

5.2. Instruments

5.2.1. Imager And Sounder

Numerical weather prediction and forecasting models are moving towards improved spatial and temporal resolution for a variety of models. One instrument option for MEO is based on combining the capabilities of two NASA-developed instruments – the Moderate Resolution Imaging Spectroradiometer (MODIS) with those of the Atmospheric Infrared Sounder (AIRS). The MODIS instrument is aboard both the NASA Earth Observation System (EOS) Terra and Aqua environmental, weather and climate research satellites. The MODIS instrument provides high radiometric sensitivity in 36 spectral bands ranging in wavelength from 0.37 µm to 14.4 µm. The AIRS instrument, with spectral coverage from 3.7 to 15.4 µm, is the first high-spectral-resolution infrared sounder developed by NASA in support of operational weather forecasting by NOAA. Design studies are in progress for development of such an integrated instrument with capabilities that exceed those of both the ABI and HES instruments planned for GOES-R.

5.2.2. Microwave Radiometer

Microwave sounding radiometers historically have been designed as real aperture systems, where the narrow receiving “beam” required for high resolution sounding as well as imaging applications is achieved with an antenna subsystem that typically uses a parabolic reflector to focus the beam. Diffraction effects in the effective aperture formed by the reflector limit the spatial resolution. Aperture synthesis, however, is an approach that does not suffer from the limitations of a real aperture system; it uses an array of receivers to form an equivalent aperture – typically only sparsely filled array of receivers and uses on-board signal processing to measure the phase properties of the radiometric field.

As an extension of a GEO microwave synthetic thinned aperture radiometer (GeoSTAR) sounder study performed by JPL under contract to NOAA, an initial assessment for aperture synthesis in MEO was performed. The objective is to add microwave sounding capabilities to future systems such as GOES-R, both to complement GOES infrared sounding systems (such as the Hyperspectral Environmental Suite – HES) and to provide all-weather standalone microwave soundings (Dittberner, et al., 2004). For a standalone capability, GeoSTAR can be deployed on a separate platform, but to complement an IR sounder it is important to have the same field of regard, preferably on the same platform; this is the option that the study is proposing, if at all tenable at the current stage of GOES-R.

At MEO, although it would be possible to implement a two-dimensional (i.e. synthetically thinned aperture radiometer) system such as GeoSTAR, there are aliasing issues due to the large solid angle subtended by the Earth as seen from MEO. Instead, one-dimensional approaches were considered – where along-track coverage is obtained through orbital motion (something not available in GEO). Two concepts were considered. One uses a waveguide antenna for each receiver in a rectangular array and another uses a large common cylindrical-parabolic offset reflector. Many details remain to be worked out and evaluated before definitive recommendations can be made. However, early indications are that MeoSTAR is much less complex than GeoSTAR, requires significantly less resources (i.e. mass and power) and is expected to cost significantly less and therefore may be an ideal application for MEO.

5.3. Requirements

MEO mission requirements are derived from requirements in the GOES-R Preliminary Requirements Document. The constellation of four satellites would make observations over the entire range within 60 degrees of the ground track, and include interleaving hemispheric (full disk), synoptic (regional CONUS) and mesoscale (rapid-scan) imaging. Full disc imagery data would be taken every 15 minutes, and CONUS imagery data taken every 5 minutes – an equivalent GOES-R “full disc” as seen by the MEO constellation being a composite image from sensors on the multiple satellites. For severe weather activity, updated satellite imagery data covering areas at least 1000 km square area would be taken every 30 sec.

Mesoscale measurements would provide imaging and derived high-density wind products. Data bands would include visible and long- and short-wave infrared (IR) and IR water vapor (300-500 hPa) essential for NWS forecast operations, and to meet future NWS cloud, moisture, and surface observation and liquid-solid profiling requirements. Visible imagery data would have a spatial resolution of 0.5 km or better, and IR imagery data a spatial resolution of 2 km or better for all bands. IR soundings would have a spatial resolution of 10 km or smaller, with an objective of 2 km. Temperature and moisture soundings would be made over an area of 12,000 km x 12,000 km within each hour. The accuracy of Earth-location sounding data would be 2.5 km or better in both normal and rapid scan modes. The precision of temperature soundings would be within 2°C per 3 to 5 km layer or better. The precision of moisture soundings would be within 20% of the nominal reading. The four-satellite constellation would be expected to have an operational availability of at least 98%.

6. CONCLUSIONS

This MEO architecture provides the potential to provide high spatial, temporal and spectral resolution environmental data comparable to or exceeding that of NPOESS and GOES-R. MEO architecture offers several advantages for sounding; microwave is more feasible than at GEO, with better spatial resolution and better coverage. Furthermore, launch costs may be less than for GEO and revisit times are better than from LEO. However, LEO and GEO have some other advantages – namely, LEO is more suited for high spatial resolution microwave instruments, but not for requisite temporal resolution and GEO provides excellent revisit time over field of regard, but not the MEO global. The architecture study is ongoing, as the opportunities for visible/IR imaging and sounding and microwave radiometry, and a global communications backbone are considered. A draft Program Plan has been developed, and a Program Implementation Plan that would help NOAA transition into an integrated environmental system that meets current and future observational, processing and communications requirements is in progress.

ACKNOWLEDGEMENTS

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