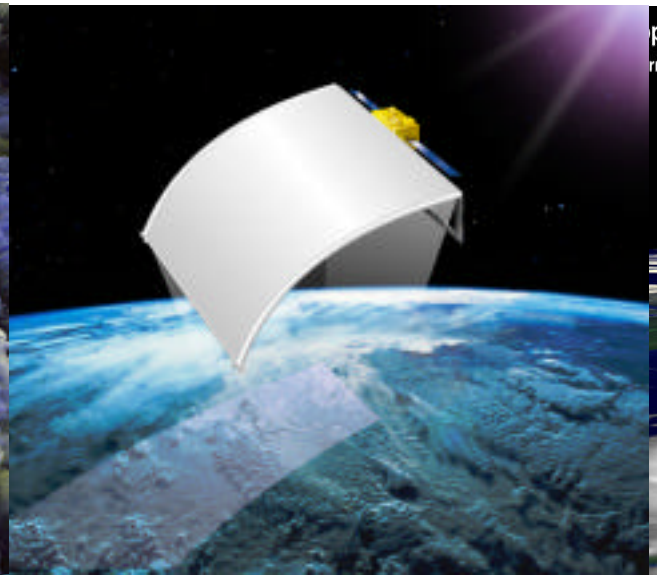
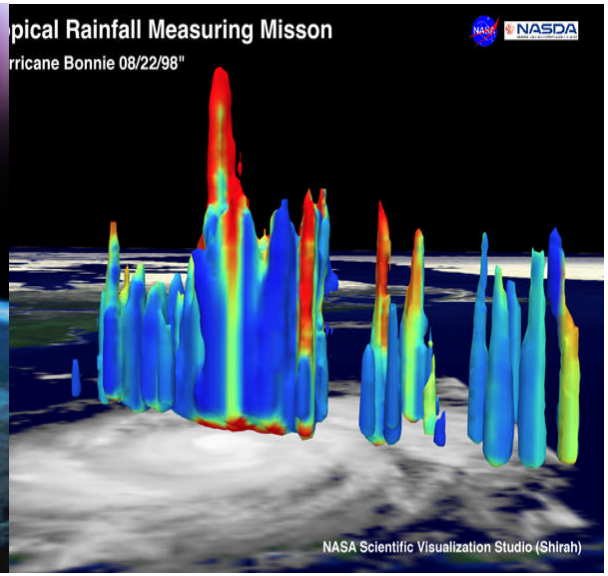
A NASA ESSP New Mission Concept:
Satellite for Prediction of Hurricane Development (PhD-Sat)
A Natural Hazards-Oriented Science Pathfinder Mission





Executive Summary

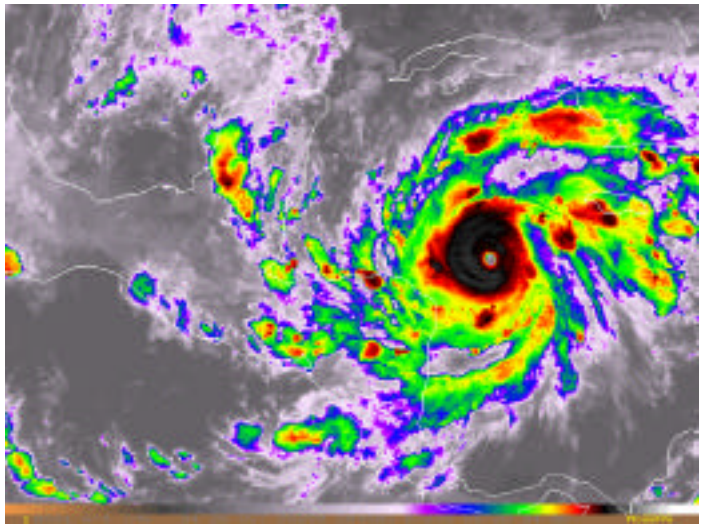
Mission Overview

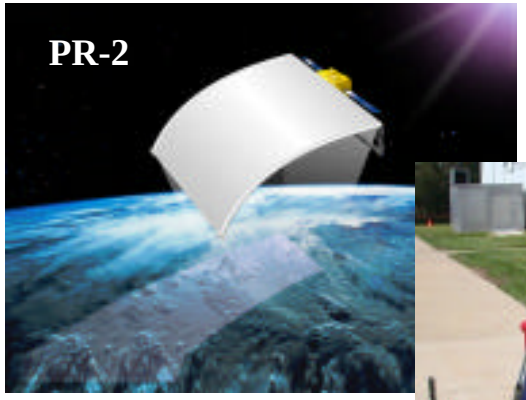
Mission Science Objectives

- Measure hurricane precipitation intensity, dynamics, and life cycle for improved model prediction of track, intensity, and rainfall
- Provide data for improved prediction of hurricane-induced floods

Mission and Instrument Characteristics

- 14/35 GHz Second-Generation Precipitation Radar (PR-2)
  - Scanning, Doppler and Dual-Pol Radar
- 10.7/37 GHz Lightweight Rainfall Radiometer
  - Scanning Synthetic Thinned Array Radiometer
- Orbit: 380 km altitude at 32.5˚ inclination
- Satellite Bus candidate: Ball RS-2000 Series
- Launch vehicle candidates: Taurus (antenna stow required) or Delta-II
- Launch: 2010





ESSP Mission Concept: Satellite for Prediction of Hurricane Development (PhD-Sat)

PhD-Sat Provisional Science Team

William M. Frank, PI (Professor, Pennsylvania State University)

NASA GSFC

1. Scott Braun: CRM-based hurricane simulation
2. Arthur Hou: global model data assimilation
3. William Lau: Madden-Julian wave dynamics and process
4. Robert Meneghini: radar rainfall retrieval
5. Caleb Principe: radiometer design-engineering
6. Eric Smith: satellite latent heating retrieval

NASA JPL-CIT

7. Steven Durden: radar microphysics retrieval & radar design-engineering
8. Ziad Haddad: combined radar-radiometer rain retrieval
9. Eastwood Im: lead radar scientist/engineer
10. Timothy Liu: wind scatterometer liaison and hurricane boundary layer circulation
11. Simone Tanelli: Doppler/polarization signal processing

NOAA AOML-HRD and CSU-CIRA

12. Peter Black (AOML-HRD): hurricane forecasting and observational analysis
13. Mark DeMaria (CSU-CIRA): hurricane forecasting and modeling
14. Frank Marks (AOML-HRD): hurricane theory and observational analysis

Academic (10 institutions)

15. Shuyi Chen (UMiami): hurricane modeling
16. David Emmitt (SWA/UVa): wind lidar liaison and large scale hurricane circulation
17. William Frank (PSU): hurricanes and tropical meteorology
18. Gregory Jenkins (PSU): cloud-precipitation microphysics and climatological properties of tropical rainfall
19. Christian Kummerow (CSU): radiometer simulation and rain retrieval
20. Michael Montgomery (CSU): theory of hurricane formation and core dynamics
21. Alberto Mugnai (ISAC-CNR): ASI liaison and radiative transfer theory
22. Elizabeth Ritchie (UNM): hurricane genesis
23. Christopher Ruf (UMich): lead radiometer scientist/engineer
24. Gregory Tripoli (UWisc): CRM-based hurricane simulation & microphysics retrieval
25. Hans Verlinde (PSU): convective processes using radar data
26. Xiaolei Zou (FSU): hurricane 4DDA & diabatic model initialization

Scientific Merit and Impact

PhD-Sat Mission addresses several NASA ESE strategic questions:

- ***Variability:*** *How are global cycling of precipitation, evaporation, and cycling of water changing?*
- ***Responses:*** *What are effects of clouds and surface hydrologic processes on Earth's climate?*
- ***Consequences:*** *How are variations in local weather, precipitation and water resources related to global climate variation?*
- ***Prediction:*** *How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?*
- ***Applications:*** *Natural Hazards relating to tropical cyclones*

PhD-Sat Mission focuses on the priorities in NASA ESE Roadmap on Weather Prediction:

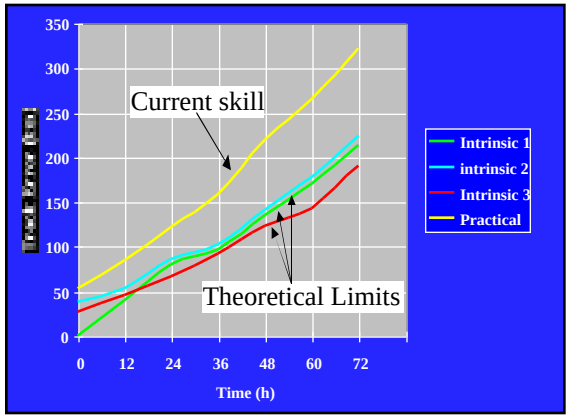
- ***Today:***
  - *3-day rainfall forecast not achievable*
  - *hurricane landfall ± 400 km at 2-3 days*
- ***NASA Goals in 2010***
  - *3-day rainfall forecast routine*
  - *hurricane landfall ± 100 km at 2-3 days*

Practical Benefits:

- *Saving of lives / enhancement of public safety*
- *Improvement of emergency response capability and reduced false-alarms*
- *Optimization of emergency resource utilization and cost benefits*
- *Mitigation of property losses*
- *Enhancement in other economic sectors (e.g., insurance coverage…)*

Current State-of-the-Art and Expected Improvement

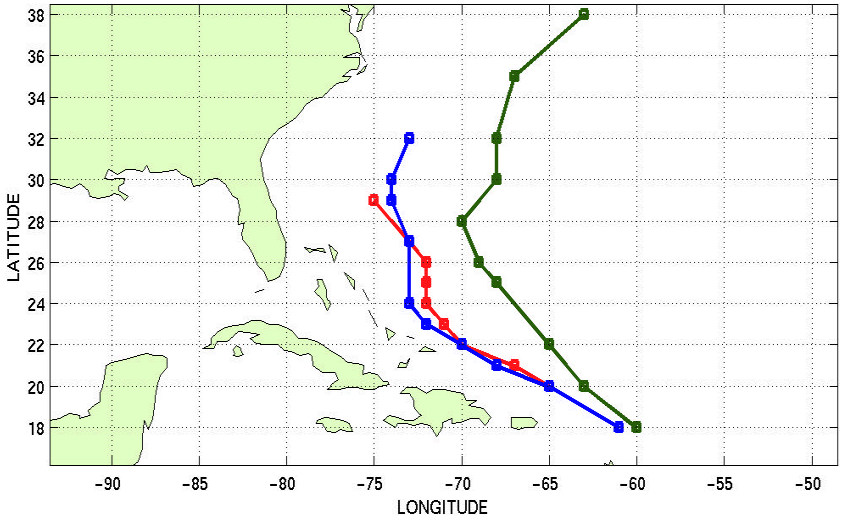
- Current track prediction capability is limited. A key factor is due to lack of detailed observations (NASA Earth Science Vision Plenary Report on Extreme Weather, 2002)
  - *Marginal precipitation prediction skill*
  - *Little, if any skill, for genesis of tropical cyclones*
  - *Inadequate wind observations in and out of clouds*
  - *Inadequate in-cloud thermodynamic, precipitation measurements*
  - *Inadequate observations of vertical structure under clouds*

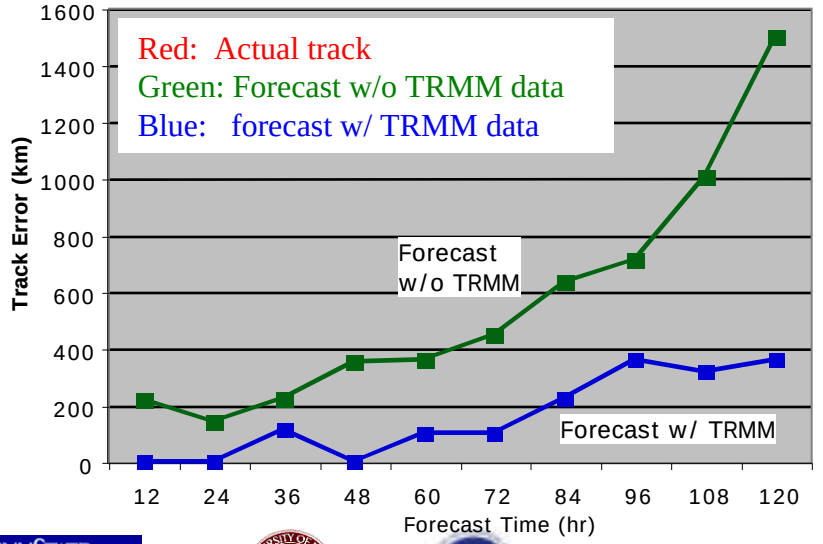


(From Abbey, Leslie and Holland, 1999).

- Hurricane Track Prediction improvement with addition of 3-D rainfall observations: A TRMM example.

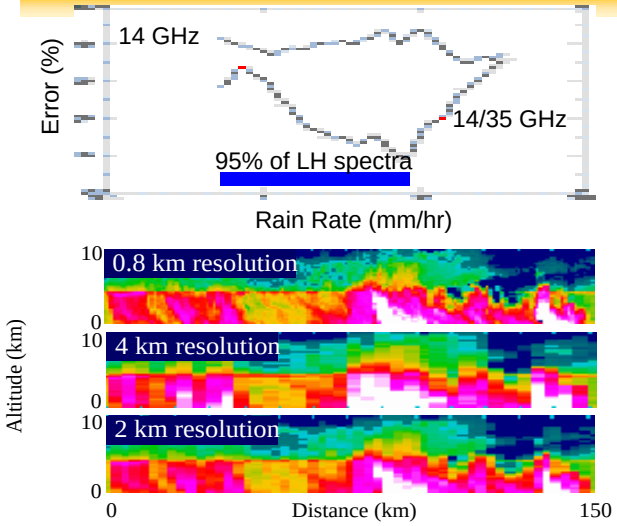
5 day forecast of Bonnie storm track





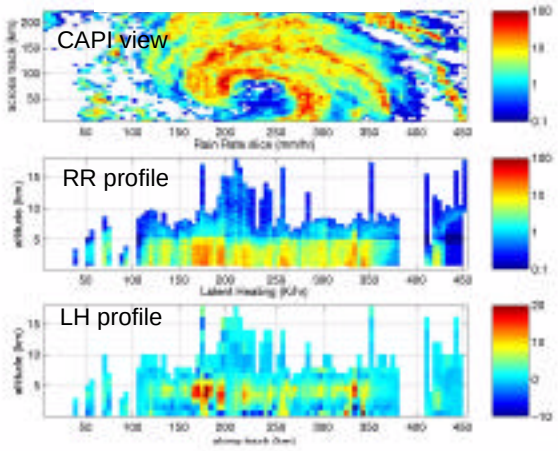
ESSP Mission Concept: Satellite for Prediction of Hurricane Development (PhD-Sat)

Some Examples of PhD-Sat Contributions to Hurricane Forecast / Studies

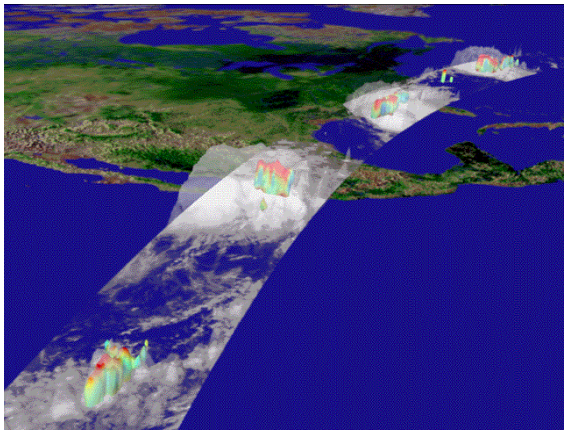


Dual-frequency and fine resolution Improve rain retrieval accuracy

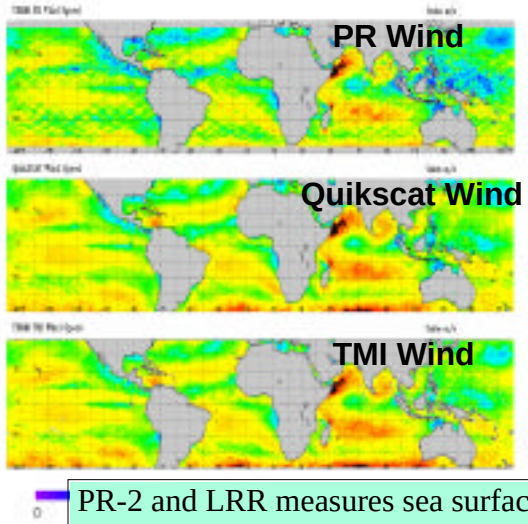
Hurricane Bonnie



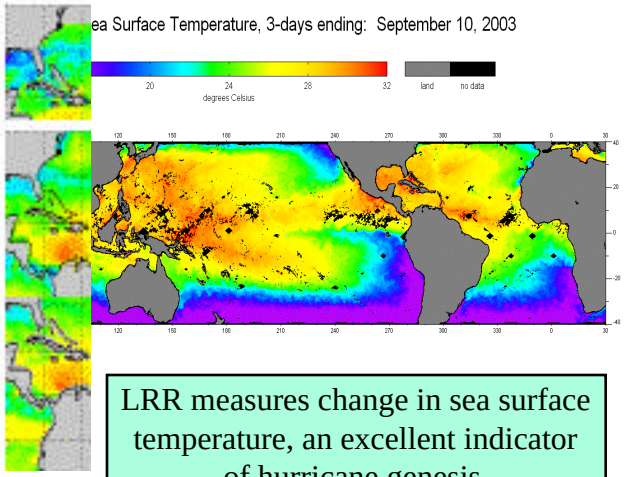
Improved measurements of latent heat, which fuels the hurricane development and intensification



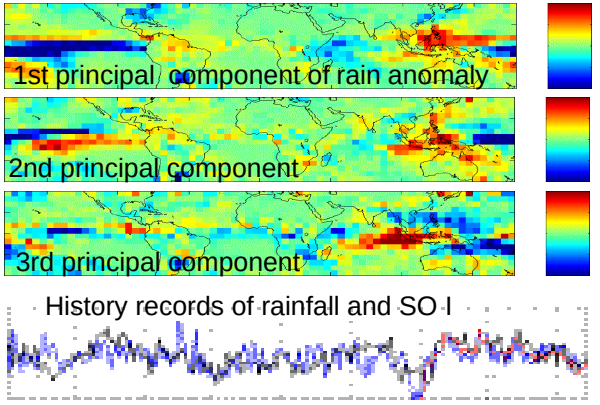
3-D observations of hurricanes in Multiple overpasses



PR-2 and LRR measures sea surface Wind in clear region of hurricane



LRR measures change in sea surface temperature, an excellent indicator of hurricane genesis



Statistical analysis shows strong correlation between rainfall variation and El Nino, which has been known to modify hurricane pattern

Traceability Between Objectives and Requirements

Science Objectives:

improve track, intensity, and rainfall predictions of landfalling tropical cyclones

Improve intensity predictions of early-stage tropical cyclones

Improve predictions of hurricane genesis

Relate hurricane activity to tropical waves

Scientific Measurement Requirements:

3-d structure of eyewall and convective bands

Convective/ stratiform classification

Location of liquid, ice, and mixed phase regions

Rainfall profiles

Particle sizes

Vertical motion

Latent heating

Hurricane obs.: 95%

Instrument Functional Requirements:

Radar:

- ***Dual-frequency (14/35 GHz)***
- ***Dual-polarization (co-pol and cross-pol)***
- ***Doppler (1 m/s precision)***
- ***wide accessible swath (440 km)***
- ***2.5 km spatial resolution***

Radiometer:

- ***Beams matched with radar for radar path attenuation estimates***
- ***wide accessible swath (760 km)***
- ***Dual-frequency (11/37 GHz)***

Mission Requirements:

3 yr lifetime

32.5 degree inclination orbit

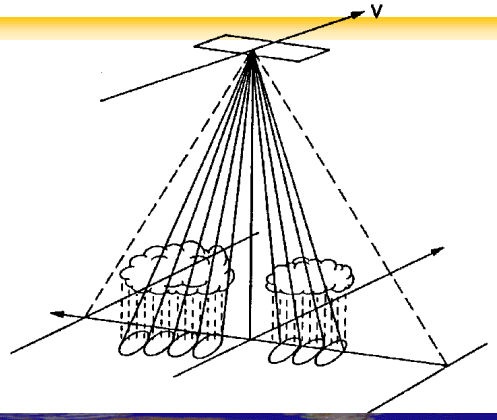
380 km altitude

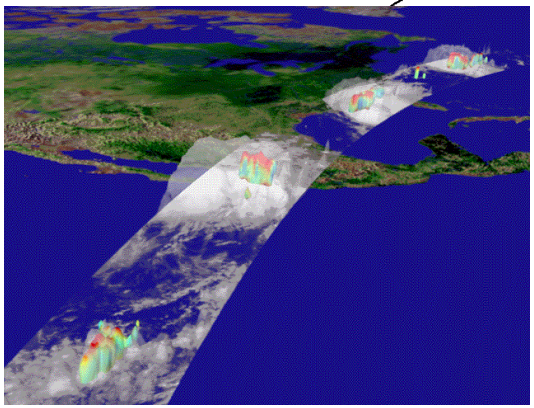
X-band downlink

Delta II or Taurus launch

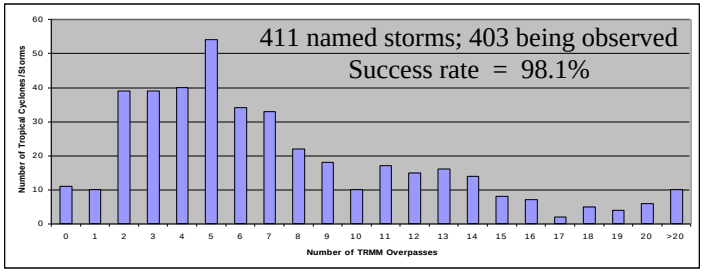
PhD-Sat Mission Concept: Space Segment

- 3-year observations of hurricanes and tropical storms
  - 32.5˚ inclination; 380 km altitude
  - > 98 % observations of all tropical storm globally
- 14 GHz and 35 GHz dual-frequency radar
  - Deployable antenna reflector with matched beams:
    - 4 m x 4.3 m (3 panels)
    - Horizontal resolution: 2.5 km @ h=380 km
  - ± 30˚scan, ~440 km swath @ h=380 km
  - Simultaneous HH and HV polarization
  - On-board, real-time pulse compression and Doppler processing
    - 250 m vertical resolution
  - Transmit peak power: 640 W @ 14 GHz; 280 W @ 35 GHz
  - Sensitivity: 6 dBZ @ 14 GHz; 2 dBZ @ 35 GHz
  - 14-GHz vertical Doppler meas. @ 1 m/s precision
  - Mass: 280 kg; Ave. power: 280 W; Data Rate: 750 kbps
- 10.7 GHz and 37 GHz dual-frequency radar
  - 2 m x 2 m thin-array synthetic antenna
    - Horizontal resolutions: 5 - 8 km
  - ± 45˚scan, ~760 km swath @ h=380 km
  - Temperature precision: < 1˚
  - Mass: 90 kg; Ave. power: 69 W; Data Rate: 61 kbps



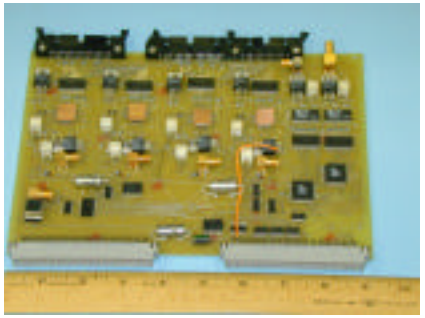


TRMM statistics: 11/97 - 6/03

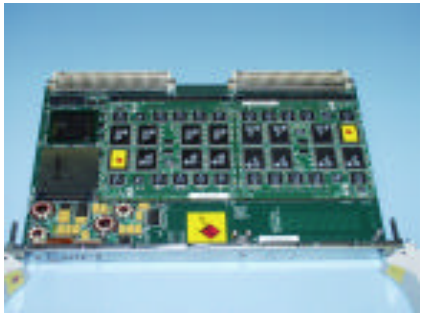


Significant Mission/Technology Heritages

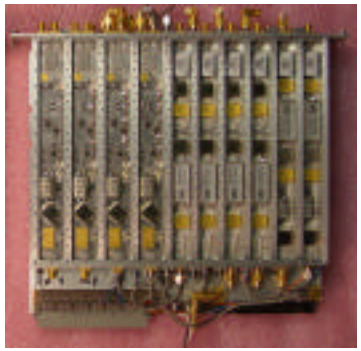
- *Mission design builds upon experience with TRMM, CloudSat, & GPM.*
- *Leverage of spaceborne instrument technologies developed since 1999 through five IIPs, one ACT, and two AIST awards from NASA ESE.*
  - **Six on PR-2; two on LRR**



PR-2: A/D Converter & Variable Waveform Generator



PR-2: Real-time Data Processor (40 billion ops per sec)

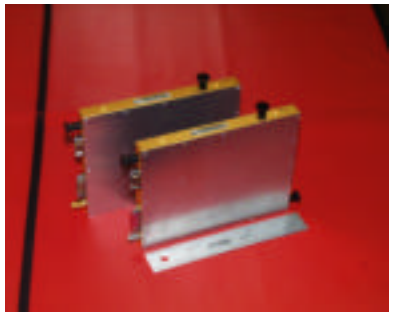


PR-2: IF/LO module (2 TX and 4 RX channels)

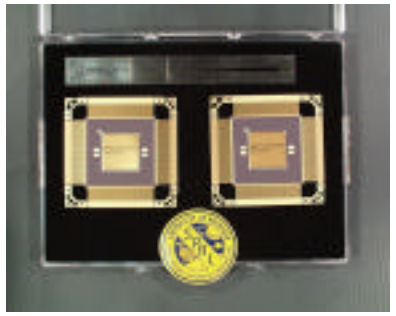
PR-2: Large cylindrical-parabolic antenna

PR-2: Ku-band antenna feed array

LRR: Prototype of X-band channel of LRR

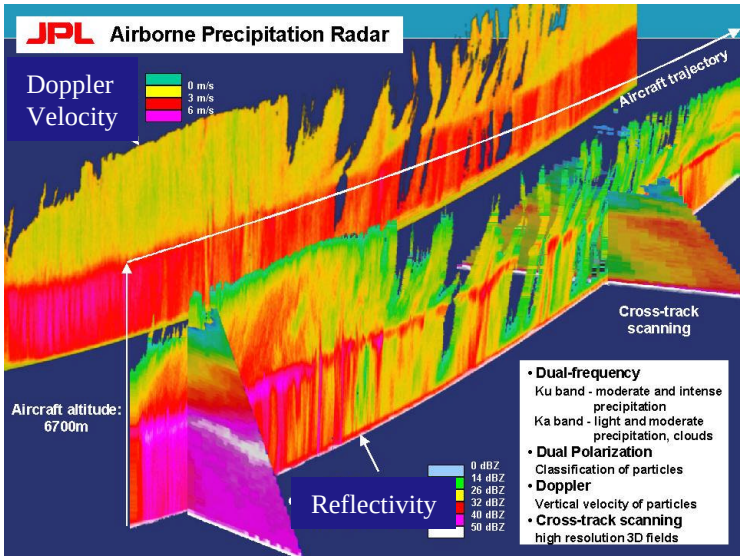


LRR: Correlation receiver with calibration and digitization.

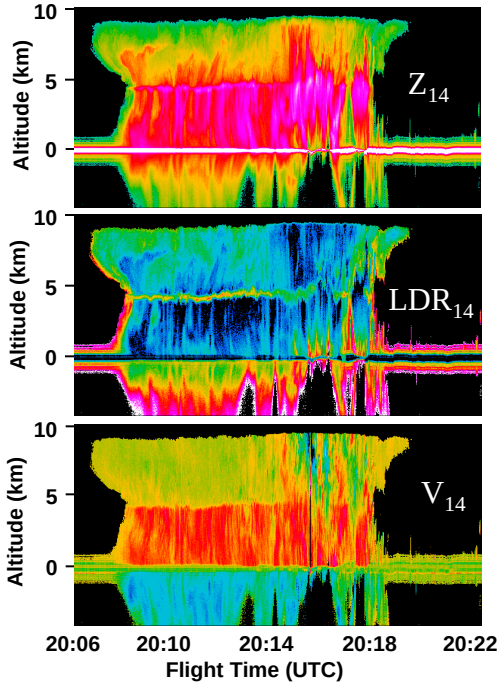


LRR: ASIC 25 channel quad demodulator and correlator

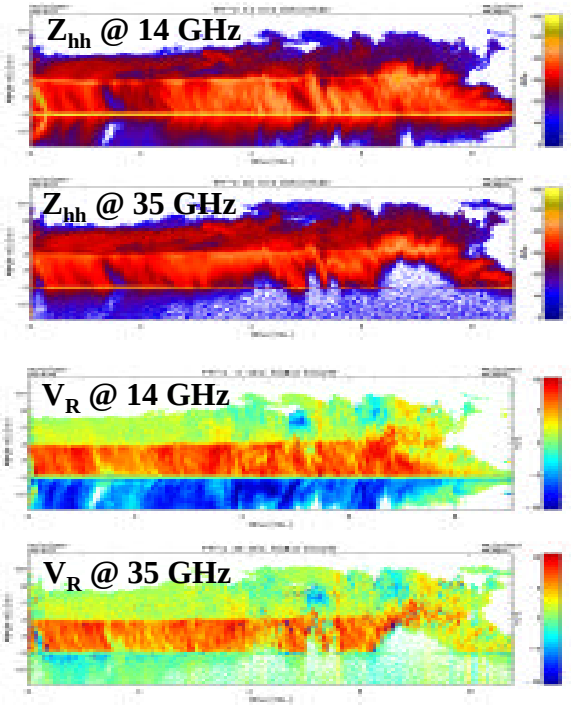
Extensive Airborne Programs and Observations to Demonstrate Proposed Measurement Approaches



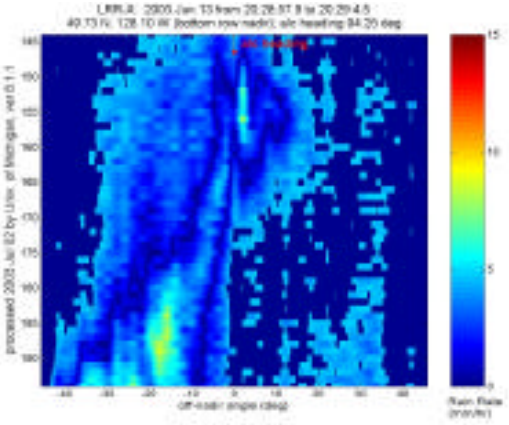
Airborne PR-2's 3-D rainfall measurements



Airborne PR-2 Observation of TC Chantal on 8/20/ 2001

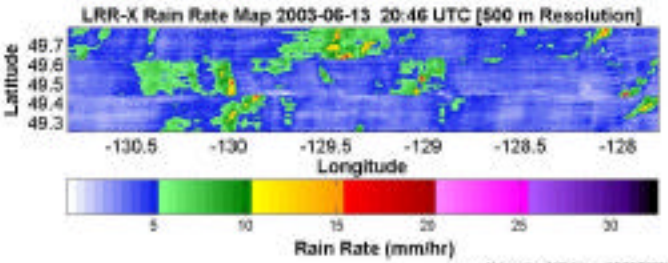


Airborne PR-2 Observation of Hurricane Humberto on 9/25/2001



Airborne X-band LRR's rain rate image on 6/13/2003

Airborne X-band LRR on NASA DC-8



Airborne X-band LRR's rain rate map on 6/13/2003

PhD-Sat Mission Concept: Telecommunication

- Requirement:
  - Provide a high rate science return link (150 Mbps at X-band) from the satellite to Western Australia and Santiago stations of the Universal Space Network (USN).
  - Return 72 Gbits/day – equivalent of 2 average 4 minute passes
  - Provide S-Band command, tracking and engineering downlink capability
- Design:
  - Single string S-Band transponder with a 5 watt power amplifier, one Loral Conic X-Band QPSK transmitter with a 6 watt power amplifier, 2 S-Band LGAs connected through a coupler, an X-Band LGA (~0dBi), a S-Band diplexer and cabling
    - No articulation for telecom contacts.
  - The X-Band high rate link has a data margin of 3dB
  - BER of 10-6
  - S-Band command link margin > 10 dB; telemetry link margin > 6 dB
- Technology:
  - No new technology; low risk

PhD-Sat Mission Concept: Ground Operations

- Requirement:
  - Total data volume: 72 Gbits per day
  - X-band data return current capabilities are 150 Mbps .
- Design:
  - X-band to ground stations at 150Mbps current capabilities. At 150Mbps requires 2 passes of 4 minutes duration per day for data return.
  - Use Santiago Chile and Western Australia USN stations to be flexible enough to not need every contact.
  - Data transferred from the Ground Station to Goddard Space Flight facility where network and mission control is managed. Instrument data processed to Level 0 and forwarded on to the customer for additional processing.
- No new technology; low risk

- Science Processing:
  - PhD-Sat L-1 and L-2 science processing and distribution at GSFC
    - Leverage of GSFC TRMM and GPM facilities and heritage.
  - Distribution to Science Team members for model forecast studies (TBR)

JPL Team-X Mission Resource Estimates

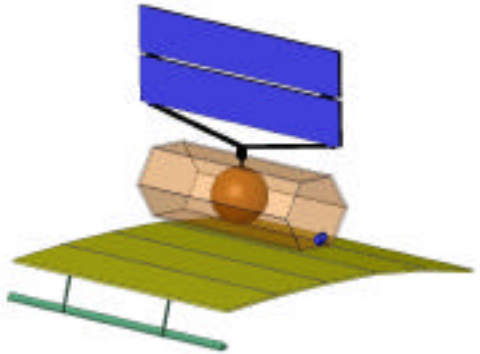
Start Date:	8/22/2003												
Stabilization - cruise	3-Axis				Pointing Direction - cruise	NA							
Stabilization - science	3-Axis				Pointing Direction - science	Nadir				Mission Duration	3.0	years	
										Max probe sun distance	1	AU	
Pointing Control	720	arcsec			Radiation Total Dose, krad	<4				Instrument Data Rate	800	kb/s	
Pointing Knowledge	360	arcsec			Science BER	1.0E-06				Data Storage	80.0	Gb	
Pointing Stability	150	arcsec/sec			Redundancy	Selected				Total Mission Data Volume	4E+07	Mbits	
Determined by:	Science									Maximum Link Distance	1804	km	
					Technology Cutoff	2007				Return Data Rate	150	Mb/s	

Calculated / Inputs from other systems

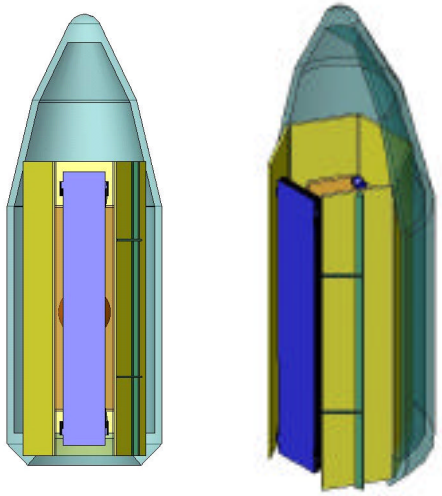
Send / Request	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Science in Sun 55 min	Mode 2 Power (W) Science in Eclipse 35 min	Mode 3 Power (W) Telecom pass >1 min (Sun or Eclipse)	Mode 4 Power (W) Orbit Correction Maneuver	Mode 5 Power (W) Launch + Assembly Resolution 3 hr	TRL	Mass Change % since last update
Payload											
Instruments	50.4%	375.0	30%	487.5	351.5	351.5	351.5	351.5	0.0		
Payload Total	50.4%	375.0	30%	487.5	351.5	351.5	351.5	351.5	0.0		
Bus											
Attitude Control	0.9%	7.0	10%	7.8	30.9	30.9	30.9	30.9	30.9		
Command & Data	2.4%	17.8	26%	22.4	51.0	51.0	51.0	51.0	51.0		
Power	6.7%	49.6	30%	64.5	33.3	33.3	40.3	36.2	12.6		
Propulsion1	3.8%	28.4	23%	35.0	18.7	18.7	18.7	30.7	18.7		
Structures & Mechanisms	23.6%	175.2	30%	227.8	0.0	0.0	0.0	0.0	0.0		
S/C Adapter	1.8%	13.5	30%	17.5							
Cabling	6.4%	47.8	30%	62.1							
Telecomm	1.3%	9.6	20%	11.5	5.5	5.5	113.8	38.8	38.8		
Thermal	2.7%	20.0	27%	25.3	54.5	54.5	54.5	54.5	54.5		
Bus Total		368.9	28%	473.9	193.8	193.8	309.1	242.0	206.4		
Spacecraft Total (Dry)		743.9	29%	961.4	545.3	545.3	660.6	593.5	206.4		
Subsystem Heritage Contingency		217.5	29%								
System Contingency		5.7	1%		163.6	163.6	198.2	178.0	61.9		
Spacecraft with Contingency		967.1			708.8	708.8	858.8	771.5	268.3		
Propellant & Pressurant1	18.1%	213.2	(50 kg RCS		1160	Delta-V, Sys 1		310	m/s		
Spacecraft Total (Wet)		1180.3									
L/V Adapter		0.0									
Launch Mass		1180.3									
Launch Vehicle Capability		1245.0	Taurus 2110					Launch C3	N/A	LV TRL	9
								Mission Unique LV Contingency	0%		
Launch Vehicle Margin		64.7	5.2%					Fairing dia., m	?	Cost Margin	
SpaceCraft Mass Margin		64.7	5.5%								

Contingencies	Mass	Power
Instruments	30%	30%
Other	0%	0%
Spacecraft Bus, dry	30%	30%

*Propulsion system slightly undersized: wet mass would be actually about 5-10kg higher (not totally converged)



PhD-Sat observatory



PhD-Sat in Taurus LV

Project Implementation Team and Potential Partners

- ***Principal Investigator: William M. Frank (Pennsylvania State University)***
- ***Science Team: 26 members***
  - ***11 from NASA and JPL; 3 from NOAA; 12 from academica***
- ***Mission Management: JPL (Pre-launch), GSFC (Post-launch)***
- ***Radar Development: JPL***
- ***Radiometer Development: GSFC / University of Michigan***
- ***Ground System: GSFC (prime), JPL and Others***
- ***Spacecraft: TBD (Ball Aerospace and Technologies Corp.)***
- ***Launch Vehicle: TBD (NASA JSC)***
- ***Potential Partner: Italy, Japan, China***

- ***NASA Science Program Manager: Ramesh Kakar***
  - ***Initial phone discussion***
  - ***Invitation to next provisional science team meeting (Oct 16-17, 2003 in Pasadena)***

- ***NASA-GSFC Partnership***
  - ***Lead scientist of this mission concept study at GSFC: Eric Smith***
  - ***This mission concept has been selected to the next phase of study***

Future Work Required to Turn Concept Study to ESSP Proposal

- Detailed science requirement definition and traceability to lower-level requirements
  - To be completed at next Science Team Meeting in Pasadena on Oct 16-17, 2003
- Definition of specific science data products at various levels
- Articulation on how the data will be used by models (be specific)
- Study/modeling results showing specifically how PhD-Sat (not TRMM) improves hurricane rainfall and intensity prediction
- Articulation of science data processing activities
  - NASA GSFC TRMM/GPM data processor center scientist will provide help
- Name of mission
  - PhD-Sat (Satellite for Prediction of Hurricane Development) is tentative
  - A competing candidate:RIEHL-Sat (Rainfall and Intensity Estimation at Hurricane Landfall)
    - Pay homage to the late Herb Riehl, considered by many to be the father of tropical meteorology and a pioneer in hurricane core analysis
  - To be decided at next Science Team Meeting
- Detailed, grass-root cost estimates
- Seek industrial partners on spacecraft and other key areas
- Seek domestic (e.g. NOAA) and international partners if it is deemed important
- Seek NASA program management support (for early HQ advocacy effort)

PhD-Sat Mission Concept Highlight

PI: William M. Frank (PSU)

NASA ESSP Mission Concept: Satellite for Prediction of Hurricane Development (PhD-Sat)

Mission Science Objectives:

- Measure hurricane precip intensity, dynamics, and life cycle for improved model prediction of track, intensity, and rainfall, and hurricane-induced floods

Address NASA Roadmap on Weather Prediction:

- **Today:**
  - 3-day rainfall forecast not achievable
  - Hurricane landfall ± 400 km at 2-3 days
- **NASA Goals in 2010**
  - 3-day rainfall forecast routine
  - Hurricane landfall ± 100 km at 2-3 days

Mission and Instrument Characteristics:

- 14/35 GHz 2nd-Generation Precipitation Radar (PR-2)
  - Scanning, Doppler and Dual-Pol Radar
- 10.7/37 GHz Lightweight Rainfall Radiometer (LRR)
  - Scanning Synthetic Thinned Array Radiometer
- Orbit: 380 km altitude at 32.5˚ inclination

Practical Benefits:

- Saving of lives / enhancement of public safety
- Improvement of emergency response capability and reduction in false-alarms
- Optimization of emergency resource utilization and cost benefits
- Mitigation of property losses
- Enhancement in other economic sectors (e.g., insurance coverage…)